Tests of discrete symmetries in K systems

Antonio Di Domenico
Dipartimento di Fisica, Sapienza Università di Roma
and INFN sezione di Roma, Italy

DISCRETE 2014 - Fourth Symposium on Prospects in the Physics of Discrete Symmetries,
2–6 December, 2014, King's College, Strand – London

K mesons – a 70 years history

1944 : first indication of a new charged particle with mass ~0.5 GeV/c^2 in cosmic rays (Leprince-Ringuet, Lheritier)
1947 : first K^0 observation in cloud chamber - V particle (Rochester, Butler)
1955 : introduction of Strangeness (Gell-Mann, Nishijima)
K^0, $\overline{K^0}$ are two distinct particles (Gell-Mann, Pais)
1955 prediction of regeneration of short-lived particle (Pais, Piccioni)
1956 Observation of long lived K_L (BNL Cosmotron)
1957 $\tau-\theta$ puzzle on spin-parity assignment, P violation in weak interactions
1960: $\Delta m = m_L - m_S$ measured from regeneration
1964: discovery of CP violation (Cronin, Fitch,…)
1970 : suppression of FCNC, $K_L \rightarrow \mu\mu$ - GIM mechanism/charm hypothesis
1972 : Kobayashi Maskawa six quark model: CP violation explained in SM

1992- 2000 : CPLear: K^0, $\overline{K^0}$ time evolution and decays, T, CP, CPT tests

1999-2003 : KTeV and NA48 (prev. E731 and NA31): direct CP violation proven : $\varepsilon'/\varepsilon \neq 0$
2003-2008 : NA48/2: charged kaon beam, search for direct CP viol.

2000-2006 : KLOE at DaΦne: first Φ factory enters in operation, V_{us} and precision tests of the SM, entangled neutral K pairs and CPT and QM tests.

K mesons – a 70 years history.....

after 70 years from the first observation one might wonder whether investigations on kaons have exhausted the information that such relatively simple but rich system can provide:

I'll try to convince you that this is not the case....

Experimental kaon talks at DISCRETE 2014

K. Massri: Precision tests of the Standard Model with kaon decays at CERN
(Thursday, Parallel 4)

M. Lenti: ChiPT tests at NA48 and NA62 experiments at CERN
(Thursday, Parallel 4)

D. Kamiska: Study of KS semileptonic decays and CPT tests with the KLOE detector
(Thursday, Parallel 4)

F. Hahn: Prospects for K+ ->pi+ nu nu observation at CERN in NA62
(Thursday, Parallel 4)

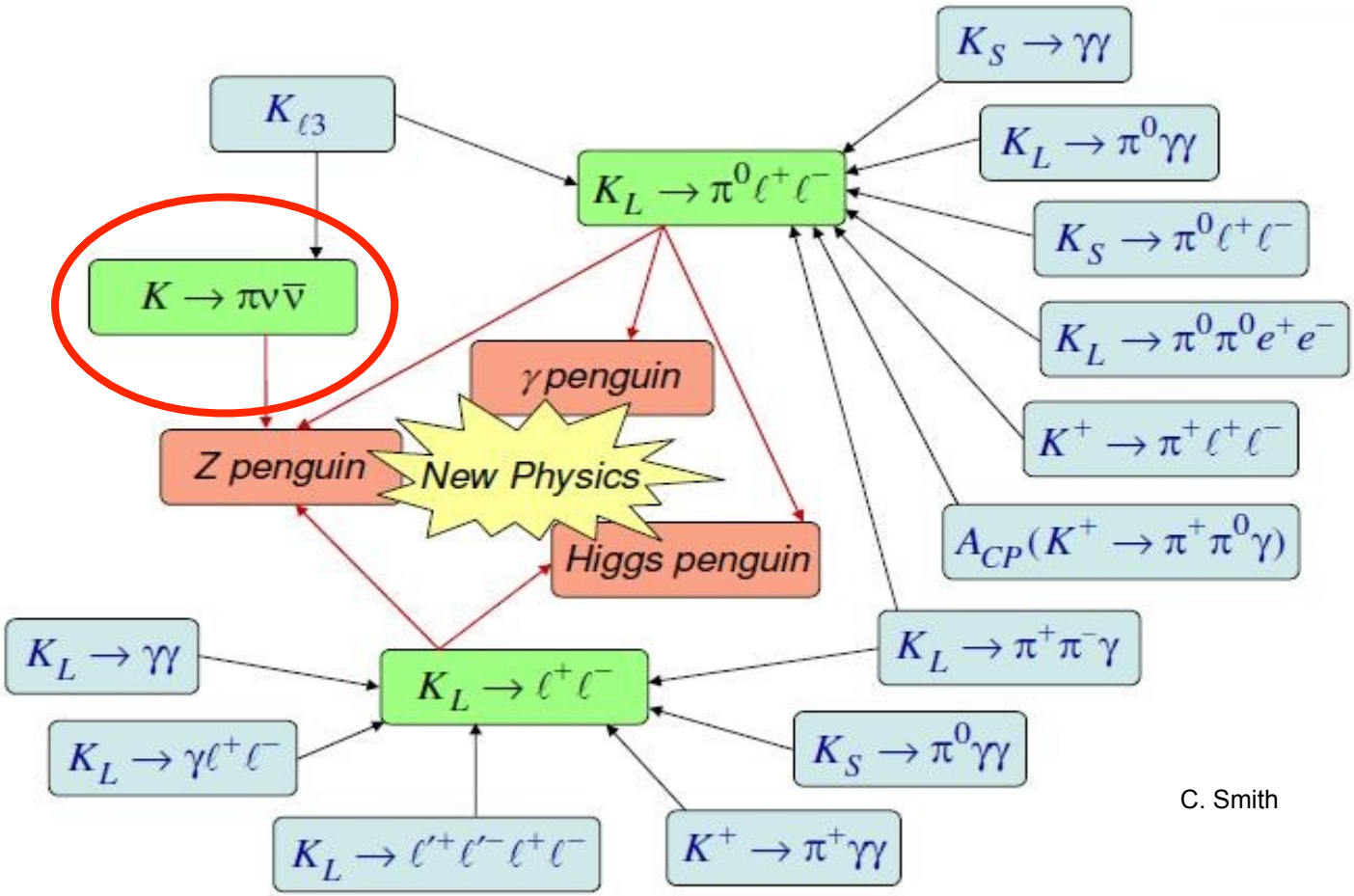
E. De Lucia: The KLOE-2 experiment at DAFNE
(Thursday or Friday, to be announced)

A. Gajos : A direct test of T symmetry in the neutral K meson system at KLOE-2
(Tuesday, Parallel 1)

Next kaon experiments at hadron machines

Rare K decays: the full picture

Switch to quantitative test of the SM; Flavor sector probing extremely high energy scales: precision frontier complementary to LHC energy frontier
Some (tiny!) BRs can be computed to very high (few percent) precision



C. Smith

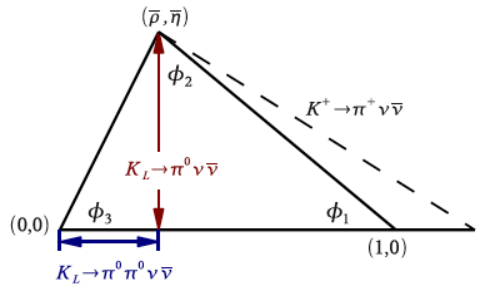
The K→ πνν decays in the Standard Model

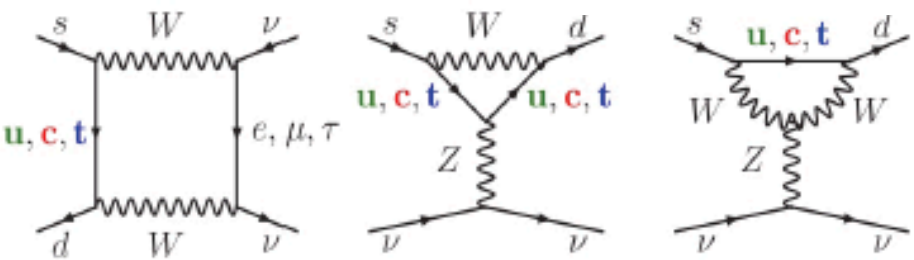
Decay (BR × 10^{10})	Theory (SM Prediction)	Experiments
$K^+ \to \pi^+ \nu \bar{\nu}$	0.781 ± 0.075 ± 0.029 [1]	1.73 + 1.15 – 1.05 [2]
$K^0 \to \pi^0 \nu \bar{\nu}$ (CPV)	0.243 ± 0.039 ± 0.006 [1]	< 260 [3]

[1] Brod, Gorbahn, Stamou: PRD83(2011) 034030, arXiv 1009.0947
[2] BNL E787/E949: PRL101 (2008) 191802, arXiv 0808.2459
[3] KEK E391a: PR D81 (2010) 072004, arXiv 0911.4789

SM predictions are extremely clean

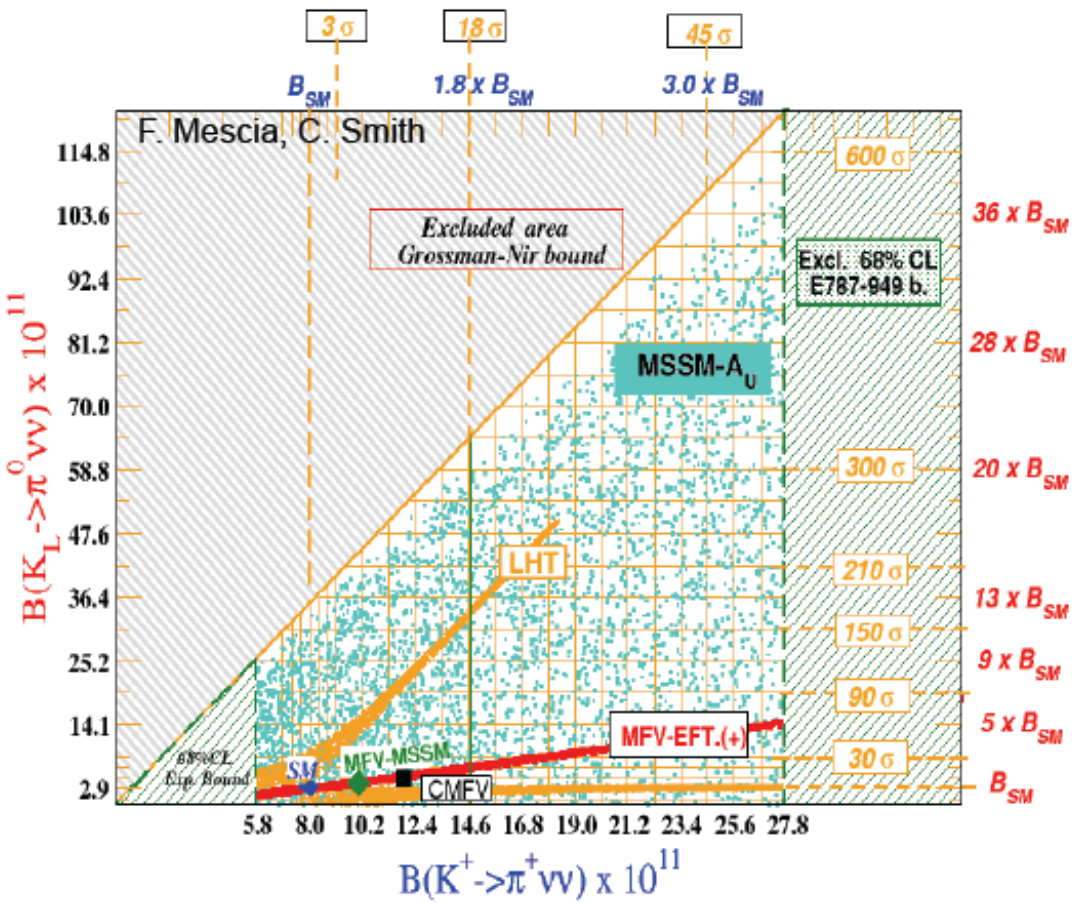
- Short Distance dynamics dominates:
  - FCNC processes only arising at loop level (Z penguins and box diagrams)
- Hadronic matrix element known from K_{e3} semileptonic decays BR via isospin rotation
- Uncertainty dominated by CKM matrix elements
- Amplitude very well predicted:
  - *clean V_{td} dependence*
  - *the BR measurement determines V_{td} without input from Lattice QCD ($\delta BR/BR \approx 10\% \longrightarrow \delta V_{td}/V_{td} \approx 7\%$)*
- Strongly suppressed in SM ($<10^{-10}$):
  - *Key role in seeking NP beyond SM*





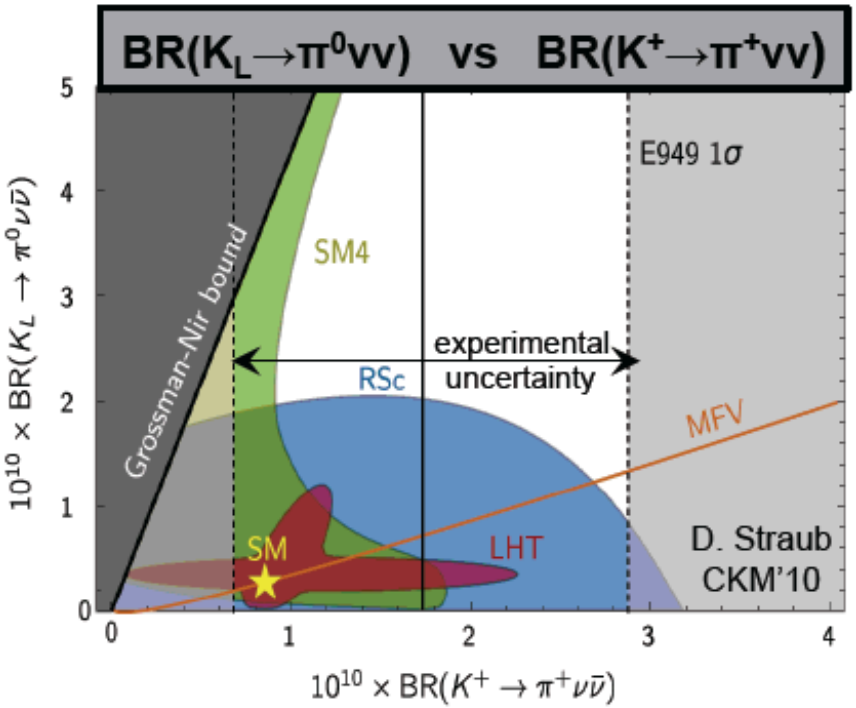
The K→ πνν decays beyond the Standard Model

- Rare K decays are highly suppressed (CKM) → highly predictive for SM extensions
- Many SM extensions predict sizeable deviations from the BR_{SM} value
- Possibility to distinguish among many different models:
  - *Chargino/$H^{\pm}$ loops (MSSM at low/large tanβ), R-parity violation (non MFV), enhanced EW Penguins, Little Higgs, extra dimensions, 4th generation, …*



NP models predicting deviations from MFV:

- *Randall-Sudrum,*
- *Littlest Higgs with T-parity,*
- *SM 4th generation*



$K^+ \rightarrow \pi^+ \nu\nu$ decay at NA62 - CERN

NA62: Beam & Detectors

Primary SPS beam: p = 400 GeV/c

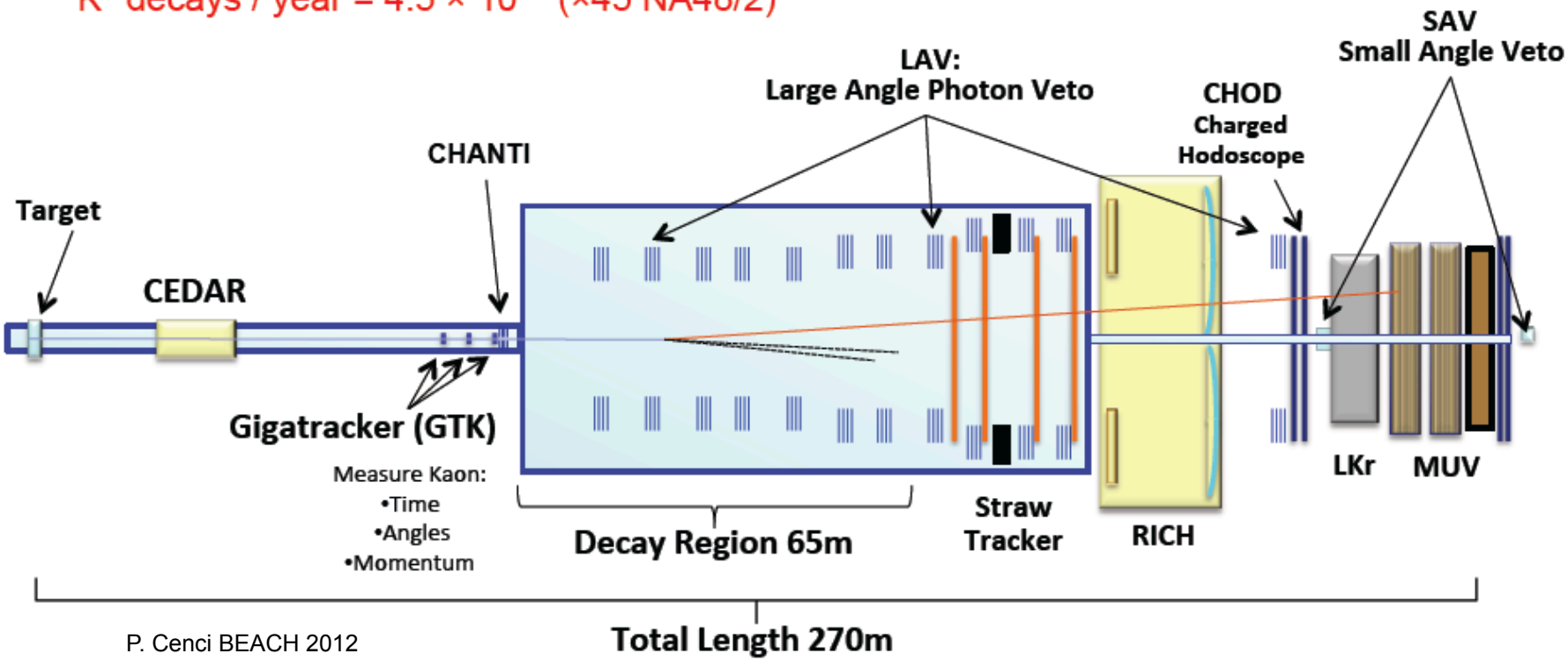
- proton/pulse 3×10^{12} (×3 NA48/2)
- duty cycle 4.8 s / 16.8 s

Secondary unseparated positive beam:

- p_K = 75 GeV/c ($\Delta p/p$~1.1%)
- $\pi/K/p$ (K^+ ~ 6% , positron free)
- K^+ decays / year = 4.5×10^{12} (×45 NA48/2)

Beam acceptance = 12 mstr (×25 NA48/2)
Area @ beam tracker = 16 cm^2
Integrated average rate = 750 MHz
Average rate @ detectors ≈ 10 MHz

Vacuum at 10^{-6} mbar to reduce beam-gas interaction (use existing NA48 decay tank)



P. Cenci BEACH 2012

NA62: guiding principles

- Kinematic rejection (m^2_{miss}):
  - Minimal amount of material budget:
    - X/X_0 kaon spectrometer (Gigatracker, Si pixel): 1.5% total
    - X/X_0 pion spectrometer (Straw Chambers in vacuum) < 2% total
- Precise timing for K-π matching:
  - Gigatracker time resolution: < 200 ps / station (beam test results on a prototype)
  - RICH time resolution: < 80 ps [NIM A 593 2008]
- High efficiency photon veto:
  - 10^{-8} π^0 veto inefficiency in $K^+ \to \pi^+\pi^0$ events
    - Offline analysis trick: $P_{\pi+} < 35$ GeV/c $\to E_{\pi0} > 40$ GeV
    - 10^{-5} LKr inefficiency for $E_\gamma > 10$ GeV
    - Hermeticity up to 50 mrad and down to 500 MeV photons (LAV detectors)
- Particle ID
  - MUV and RICH for μ–π separation → totally independent ID methods
  - LKr and RICH for π–e separation → totaly indepedent ID methods
  - Cerenkov threshold counter on beam to control the beam induced background

$K^+ \to \pi^+ \nu\nu$ decay at NA62 - CERN

Ferdinand Hahn's talk in the parallel session

GOAL: 10% precision measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$)

O(100) $K^+ \to \pi^+ \nu\bar{\nu}$ decays with ~10% background in 2 years data taking

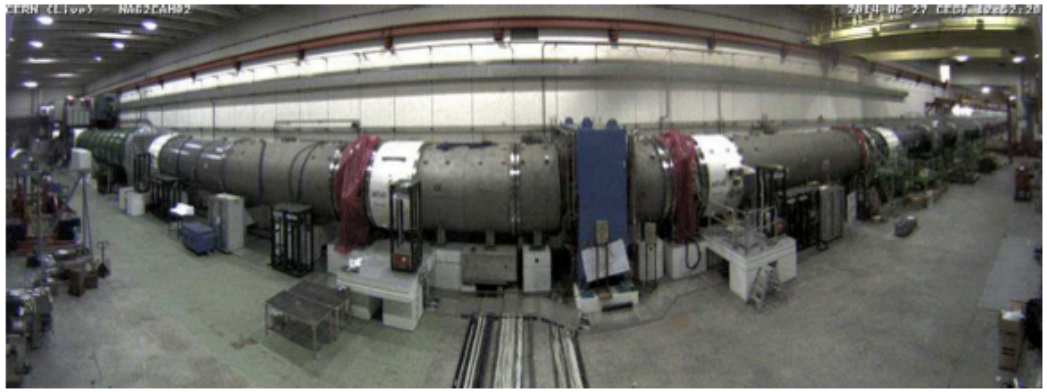
Requirements:

Statistics:

- BR(SM) ~ 8×10^{-11}
- Acceptance: 10%
- K decays: ~10^{13}

Systematics:

- $\geq 10^{12}$ background rejection
- ~10% precision on background measurement

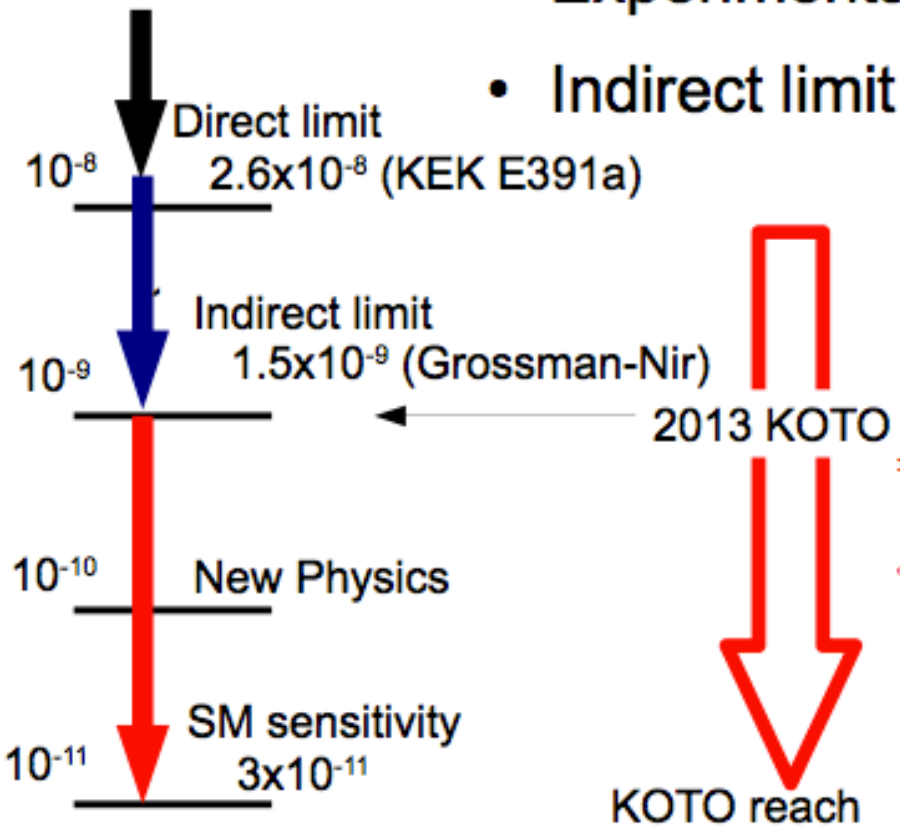


Present status:

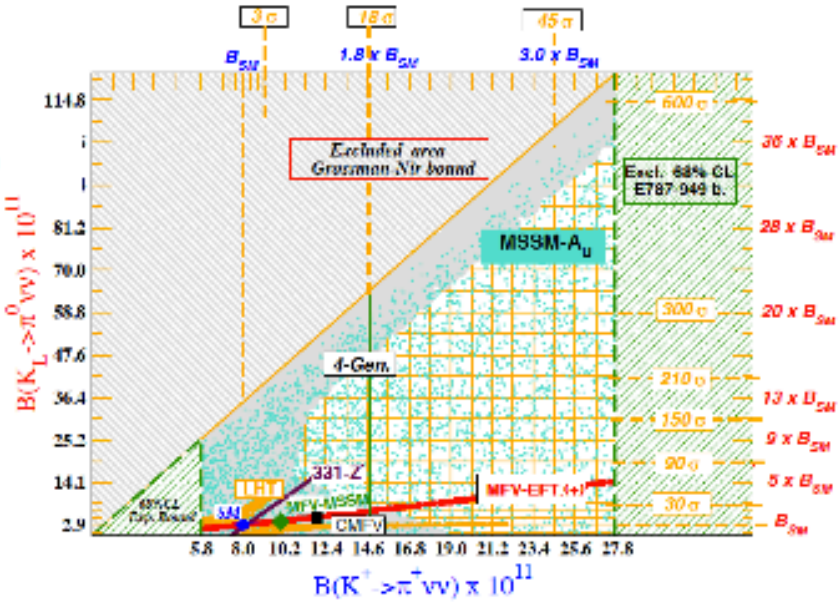
- Installation completed
- First physics run SUCCESSFULLY started 6 weeks ago!
  - completing commissioning of hardware and readout;
  - lower intensity beam;
  - reach SM sensitivity
- Nominal intensity beam in 2015-2017 for full physics run.

$K_L \rightarrow \pi^0 \nu\nu$ decay at KOTO - JPARC

- Experimental limit : 2.6×10^{-8} (KEK E391a)
- Indirect limit :1.5×10^{-9} (Grossman-Nir)

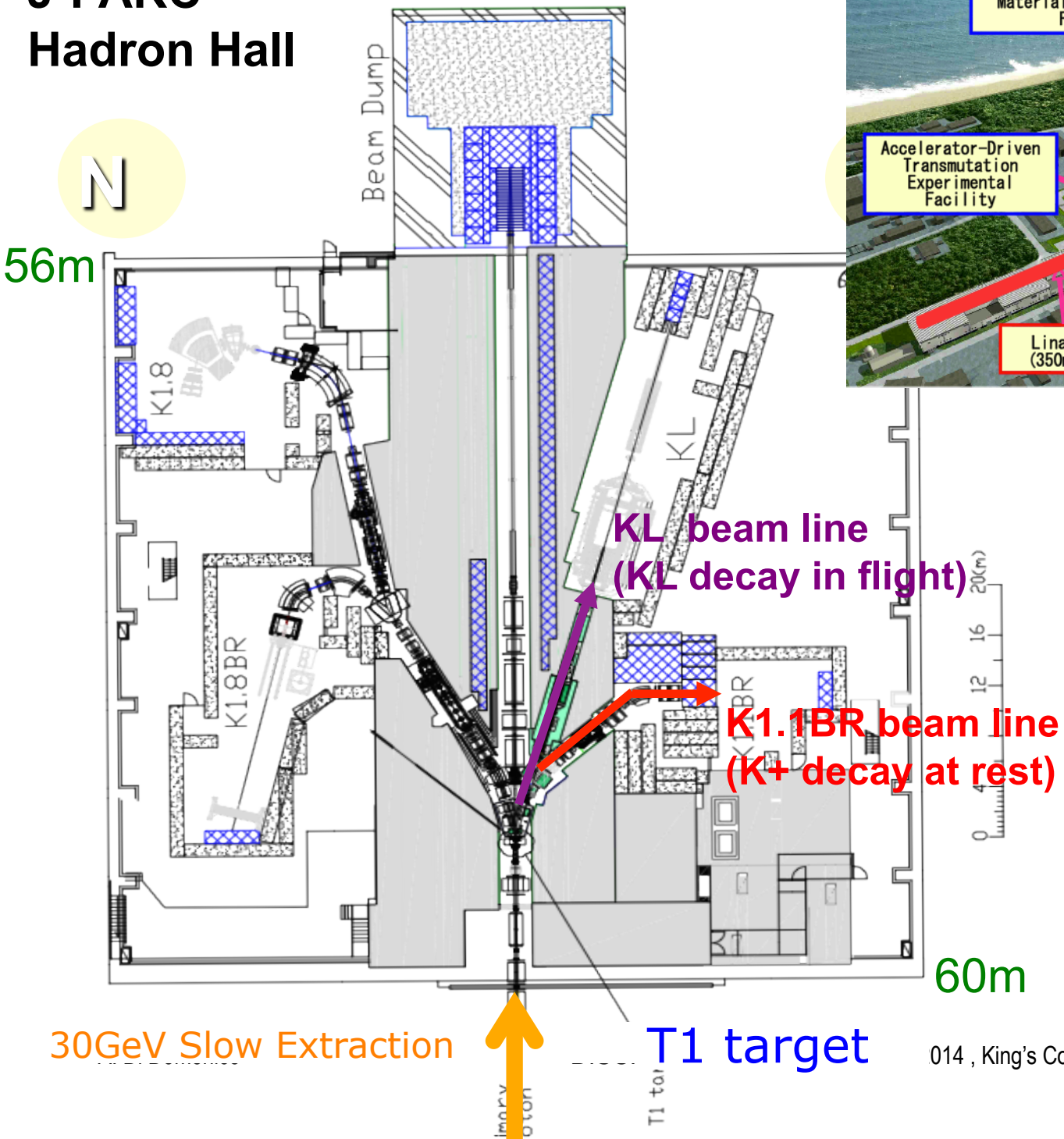


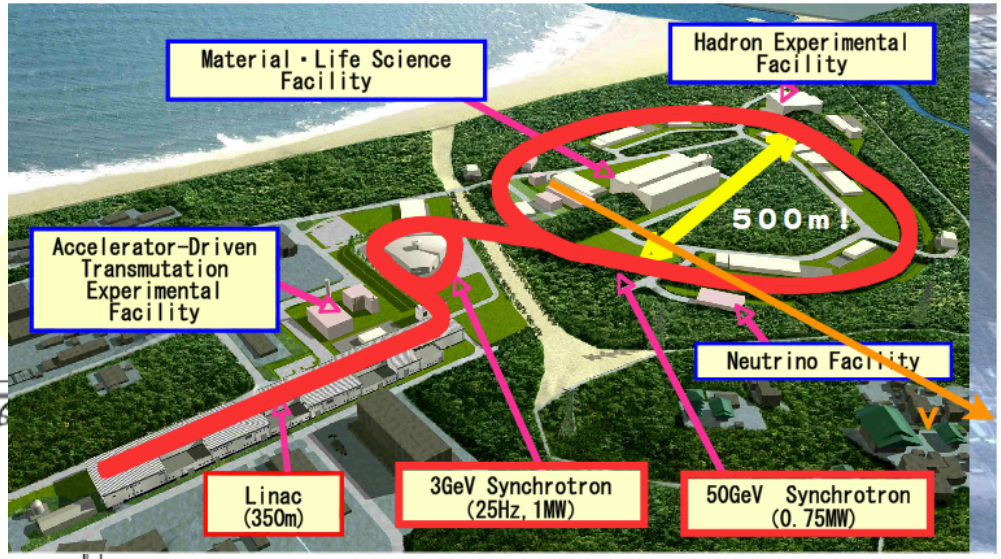
$Br(K^+ \rightarrow \pi^+ \nu\nu)$ and isospin rotation



KOTO aims to improve the sensitivity by 3 orders of magnitude (~ 3 SM events)

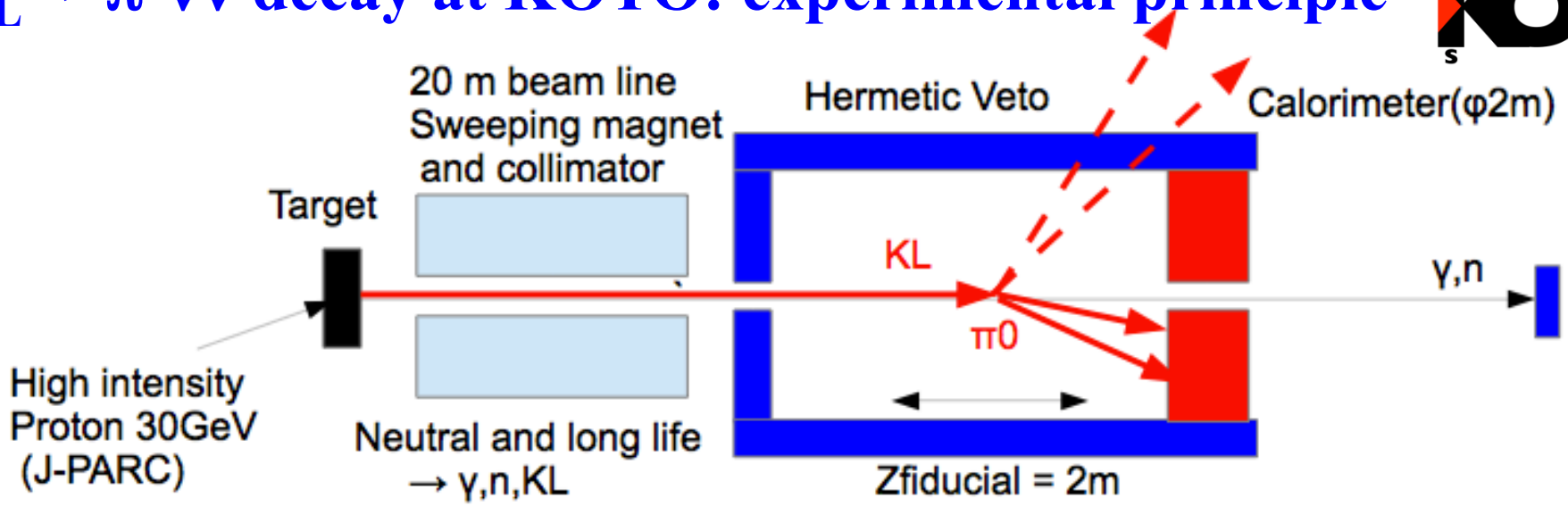
J-PARC
Hadron Hall





ハドロン実験施設
K1.1BR 実験エリアの様子

$K_L \rightarrow \pi^0 \nu\nu$ decay at KOTO: experimental principle



Pencil beam && Two gammas and nothing

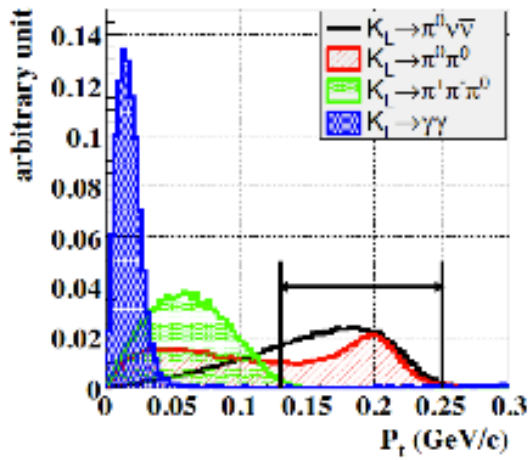
- Calorimeter and Hermetic veto

  energy and position with small beam hole and in-beam detector

- Vertex reconstruction with pi0 mass and

  vtx on z-axis assumption

  - Fiducial region in z ↔ neutron background
  - π^0 Pt reconstruction → High Pt selection



CKM2012

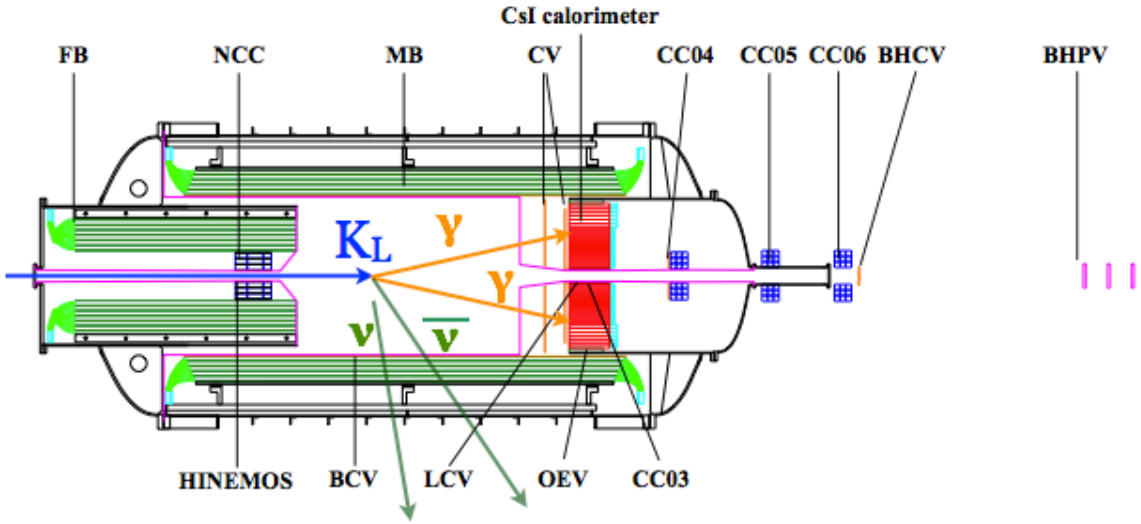
The KOTO experiment at JPARC

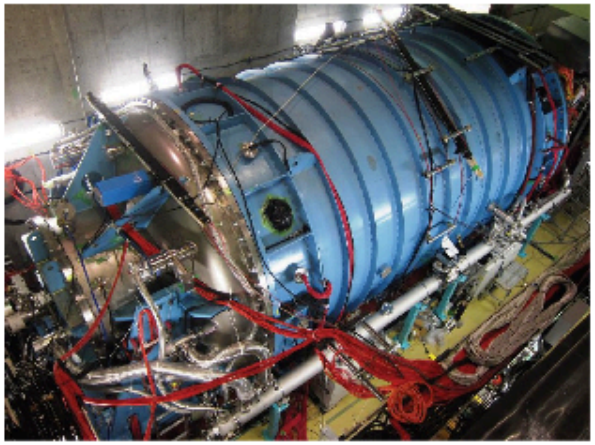
After the major Earthquake in Japan on 11 March 2011
(no damages to beam line and KOTO detector)
JPARC started re-commissioning on Dec.2011 and resumed operations on Jan.2012

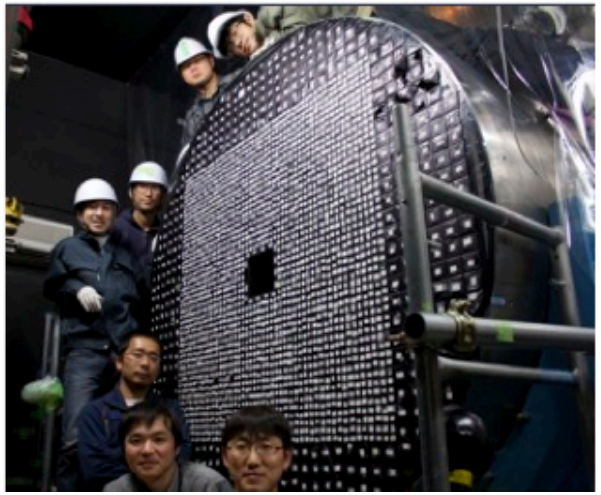
All detectors installed by May 2013

KOTO detector

CsI calorimeter + Hermetic veto system







We installed all detectors by May 2013.

Shiomi CKM2014

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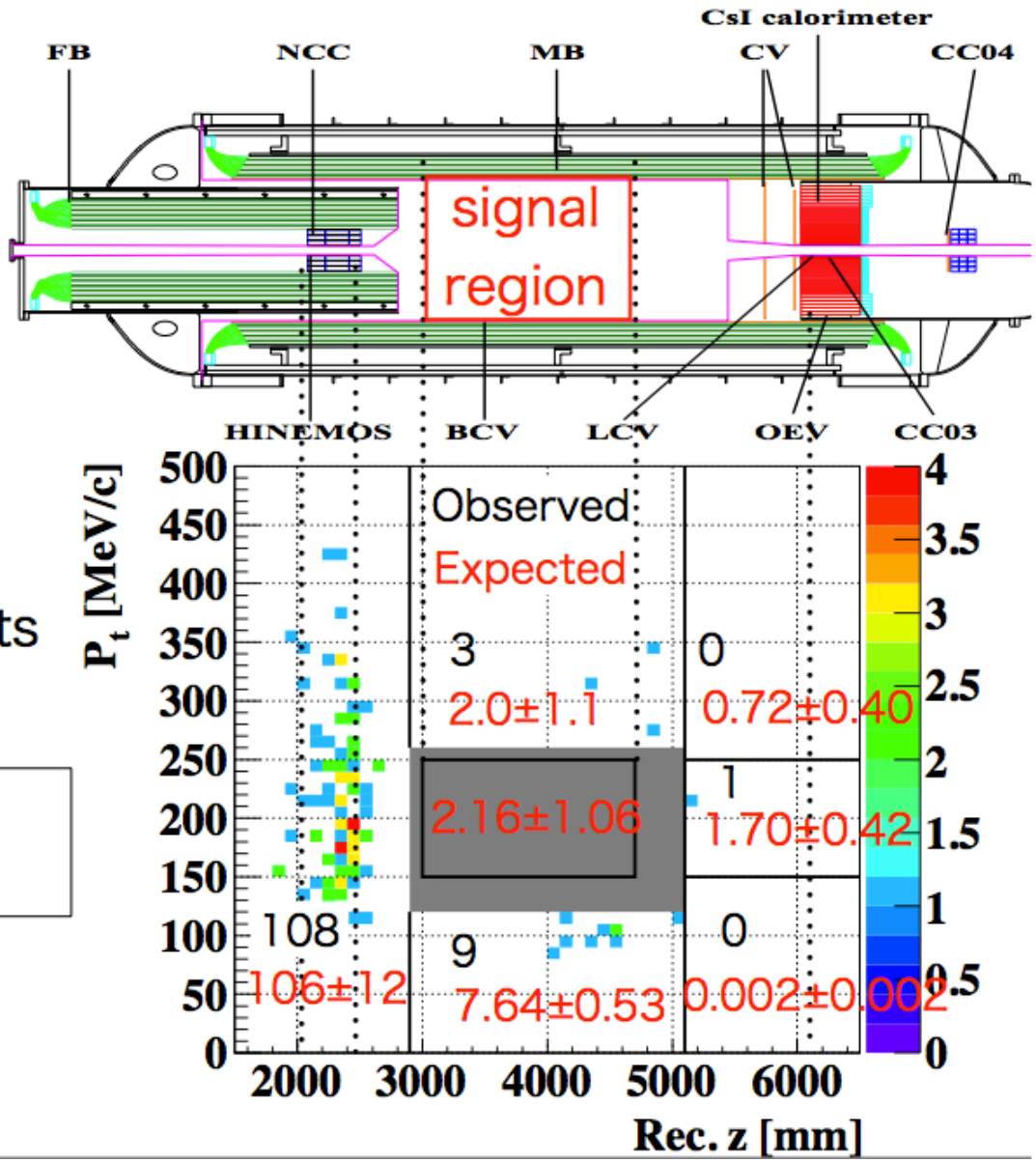
KOTO first physics run: May 17 2013
-beam power: 24 kW (10% of design intensity)
-Unfortunately, the data taking was terminated after only 100 hours due to a radiation accident in J-PARC Hadron hall
(gold target partially melted and radioactive material diffused in the atmosphere)

Preliminary analysis of the data (100h run)

EVENTS OUTSIDE THE SIGNAL BOX



P_t vs Z distribution after applying **loose** selection cuts

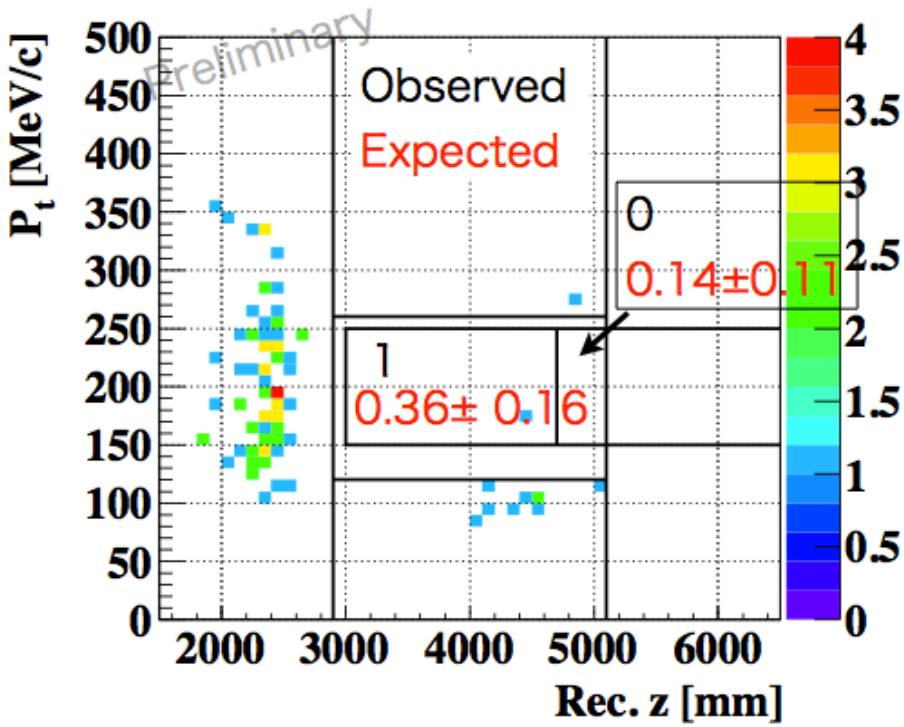
We understand the events outside the signal box well.

Shiomi CKM2014

Preliminary analysis of the data (100h run)

OPENING THE SIGNAL BOX

- One event was observed inside the signal box.
  - N_{obs} is consistent with N_{exp} statistically



Shiomi CKM2014

This result corresponds to a single event sensitivity of 1.3×10^{-8} (nearly the same as in E391a: 1.1×10^{-8})

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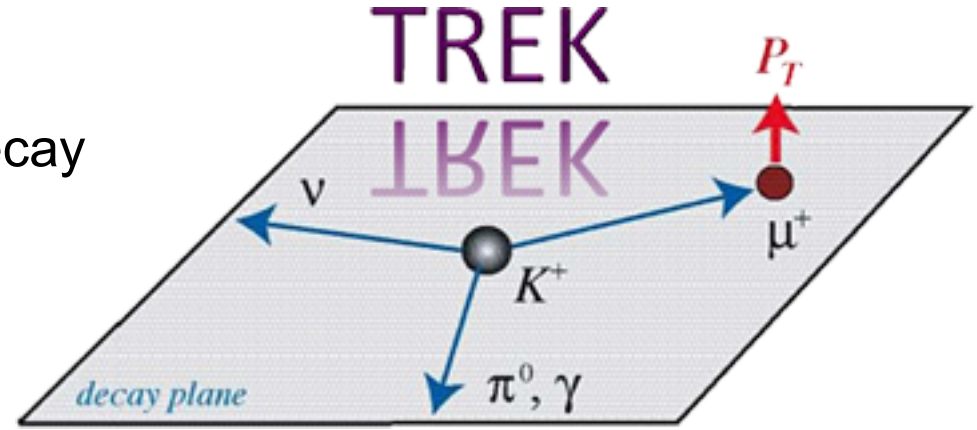
-Unfortunately, the data taking was terminated after only 100 hours due to a radiation accident in J-PARC Hadron hall (gold target partially melted and radioactive material diffused in the atmosphere)
-nearly the same sensitivity of E391a has been achieved with only 100 h run (instead of ~1000 h), turning it in a SUCCESS !
-the next run is expected to start beginning 2015 with the goal: improve background suppression (new detectors, improved analysis methods) reach higher sensitivity (x 20) wrt the first run.

TREK experiment

Transverse μ^+ polarization in $K^+ \to \pi^0 \mu^+ \upsilon$ decay
Search for a non zero T-odd observable
Pseudo-TRV due to FSI effects low (~10^{-6})
KEK E246 experiment (final 2006):

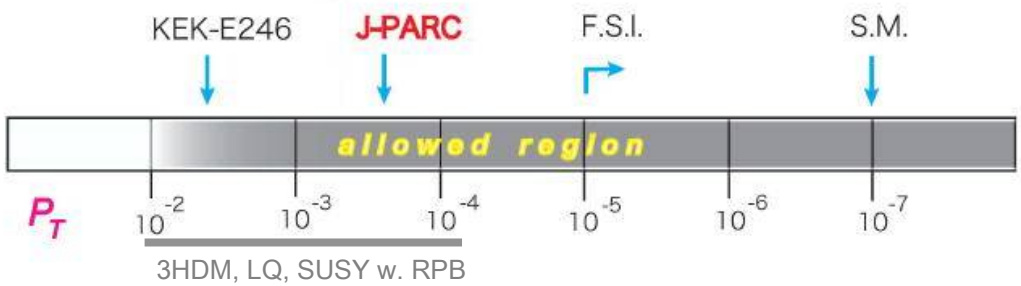
$$P_T = -0.0017 \pm 0.0023 \pm 0.0011$$

$$P_T < 5 \cdot 10^{-3} \quad (90\% CL)$$



TREK experiment Goal:

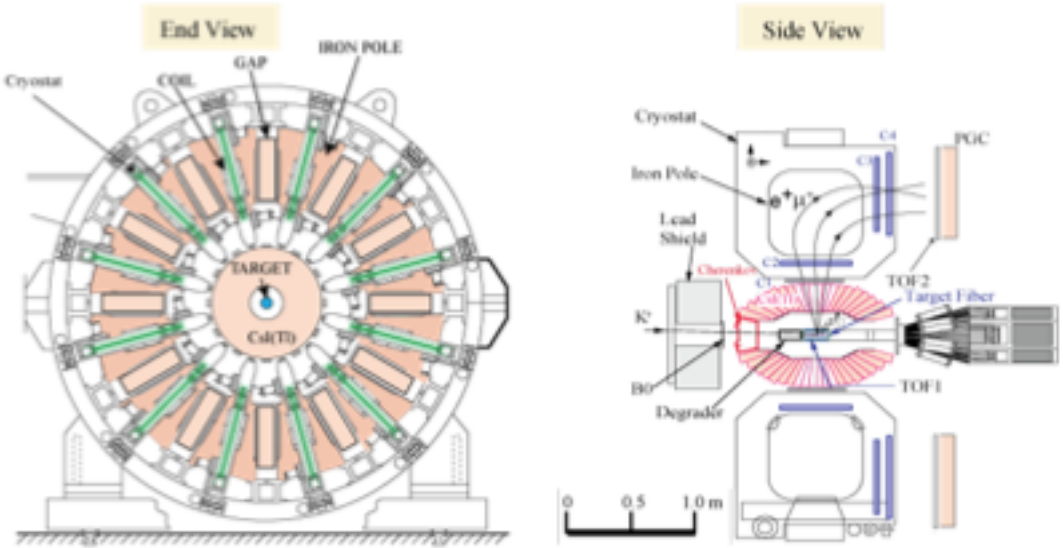
$$\sigma(P_T) \approx 10^{-4} \text{ in 1 year}$$



E36/TREK on K1.1BR beam.
The JPARC E36/TREK experiment aims to measure R_K and reduce the error by x2.

$$R_K = \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$

Physics run of E36 in Spring 2015



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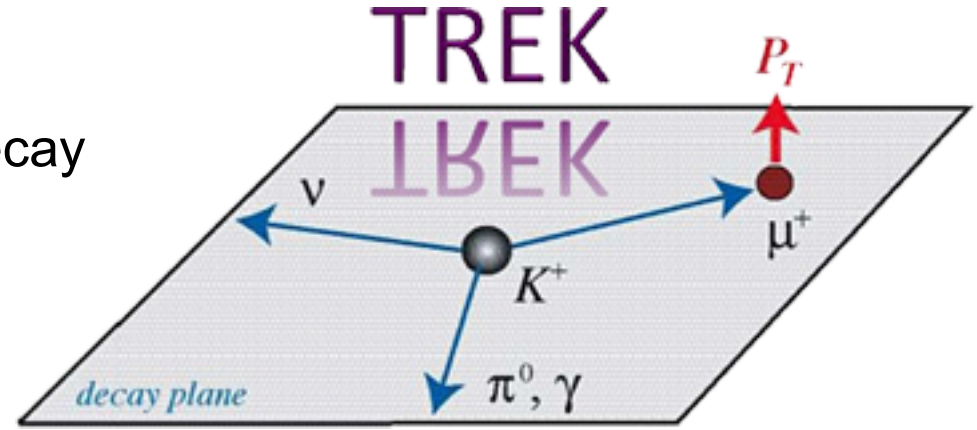

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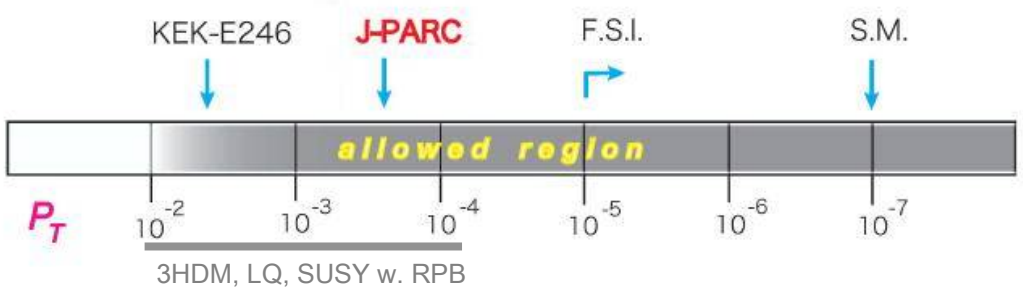

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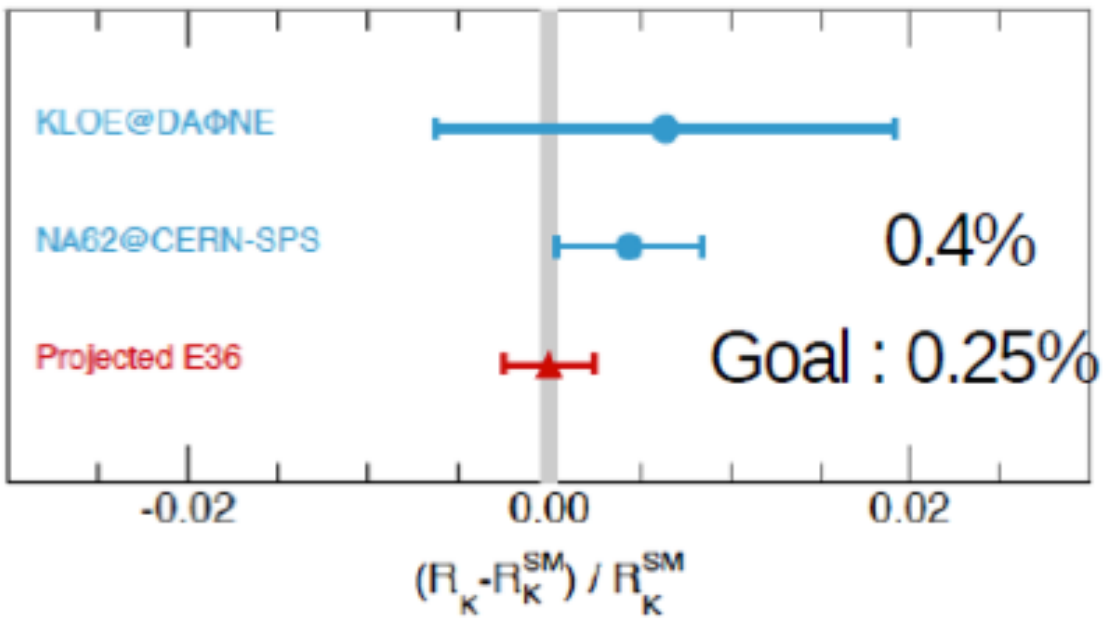
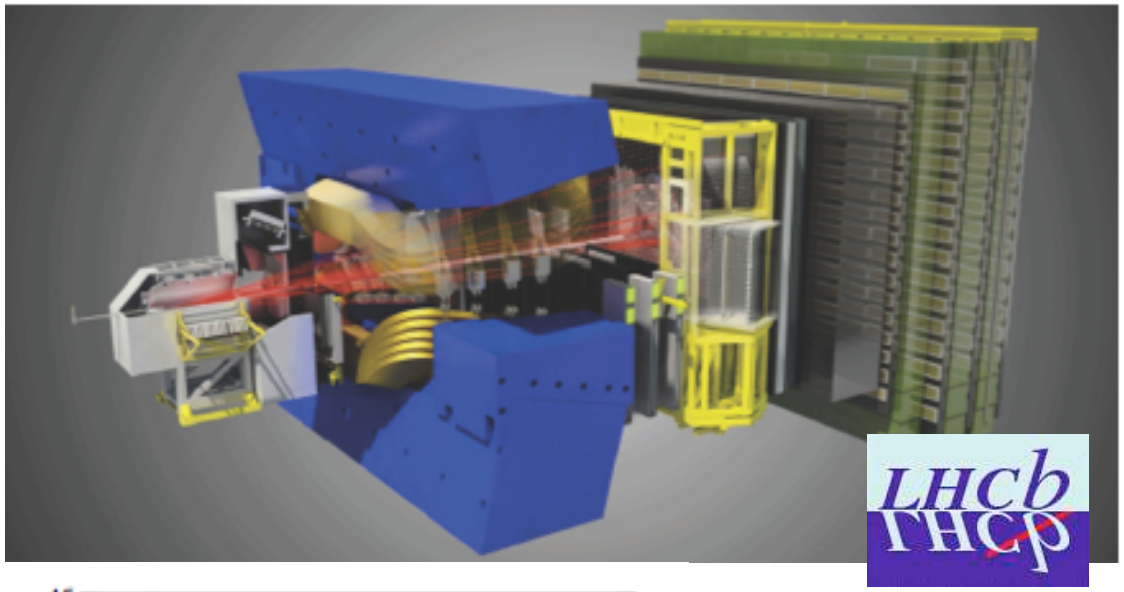


Rare K_S decays at LHCb



$K_S \to \mu^+\mu^-$

FCNC family :

SM prediction $B(K_S^0 \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$

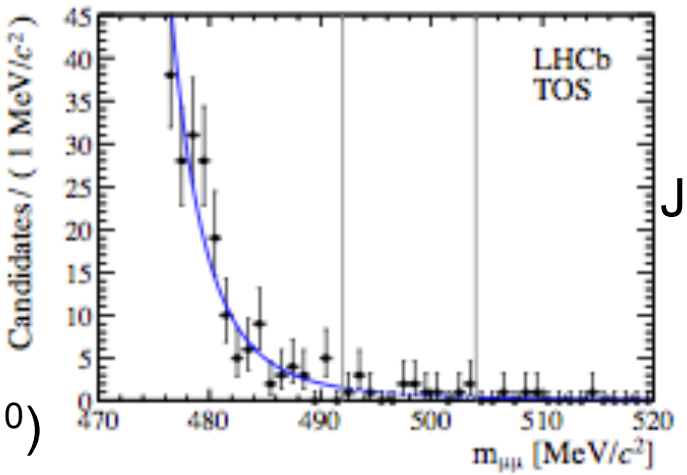
Normalisation:

$$\frac{\mathcal{B}(K_S^0 \to \mu^+\mu^-)}{\mathcal{B}(K_S^0 \to \pi^+\pi^-)} = \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu\mu}} \frac{N_{K_S^0 \to \mu^+\mu^-}}{N_{K_S^0 \to \pi^+\pi^-}}$$

We measure with 1.0 fb^{-1} :

$$B(K_S^0 \to \mu^+\mu^-) < 11(9) \times 10^{-9}$$

This limit is a factor 30 below the previous measurement !



JHEP01(2013)090

with the upgrade -> precision of $O(10^{-10})$

Considering to study also other decays: $K_S \to ee\mu\mu$, eeee, $\pi^0\mu\mu$

LHCb is not designed for kaon physics but might contribute thanks to the copious production of kaons at LHC and the excellent reconstruction capabilities;
cons: huge background to fight, and trigger limitations

The Protvino project

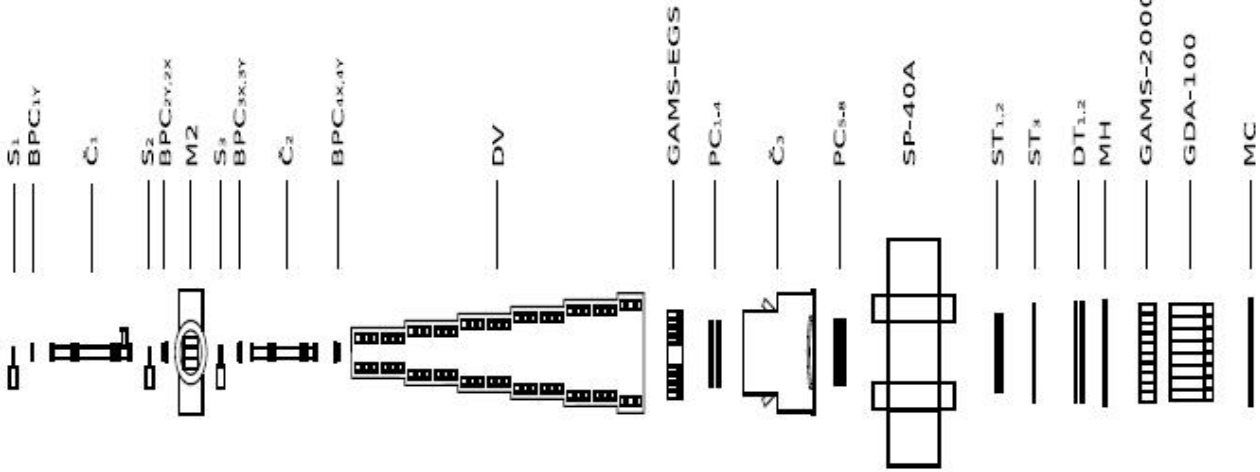
SPHINX+GAMS+ISTRA → **OKA** at Protvino:

65-70 GeV 10^{13} ppp at U-70 (38% DC)

12.5 GeV RF-separated K^+ beam **$5 \cdot 10^6$ Kpp** ($K/\pi \approx 4$)

Commissioning beam and detector with runs started 2009

10-100x improvement on ISTRA Kaon program + spectroscopy



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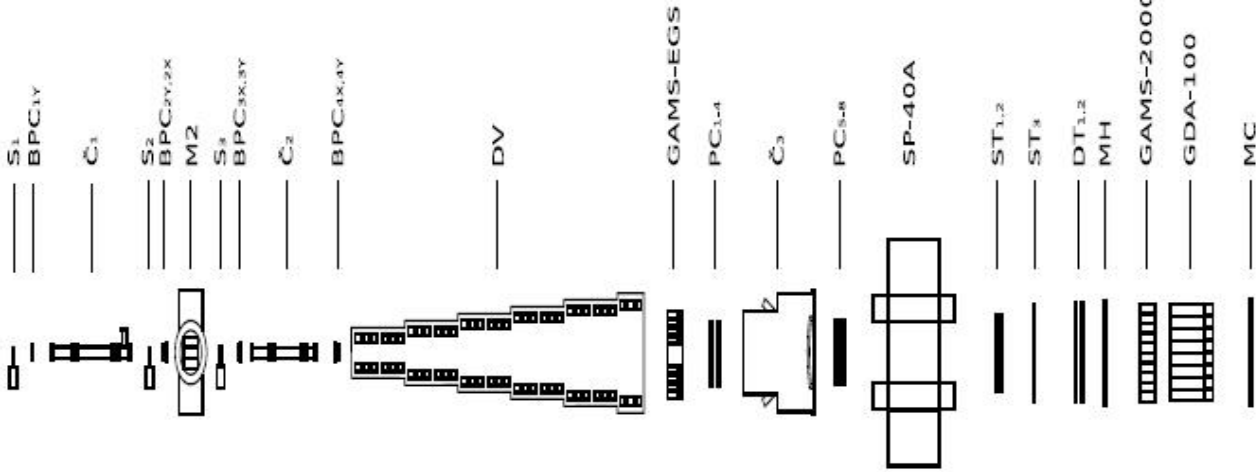


The Fermilab plan

Unfortunately the ORKA experiment in particular and kaon physics research more broadly has been terminated at Fermilab for the foreseeable future

next kaon experiment experiment at e+e- collider with entangled kaons

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- new scheme of the interaction region (crabbed waist scheme) at DAΦNE (proposal by P. Raimondi)
- increase L by a factor x 3 demonstrated by an experimental test

KLOE-2 experiment:

-extend the KLOE physics program at DAΦNE upgraded in luminosity

-Collect O(10) fb^{-1} of integrated luminosity in the next 2-3 years

Physics program (see **EPJC 68 (2010) 619-681**)

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

Detector upgrade:

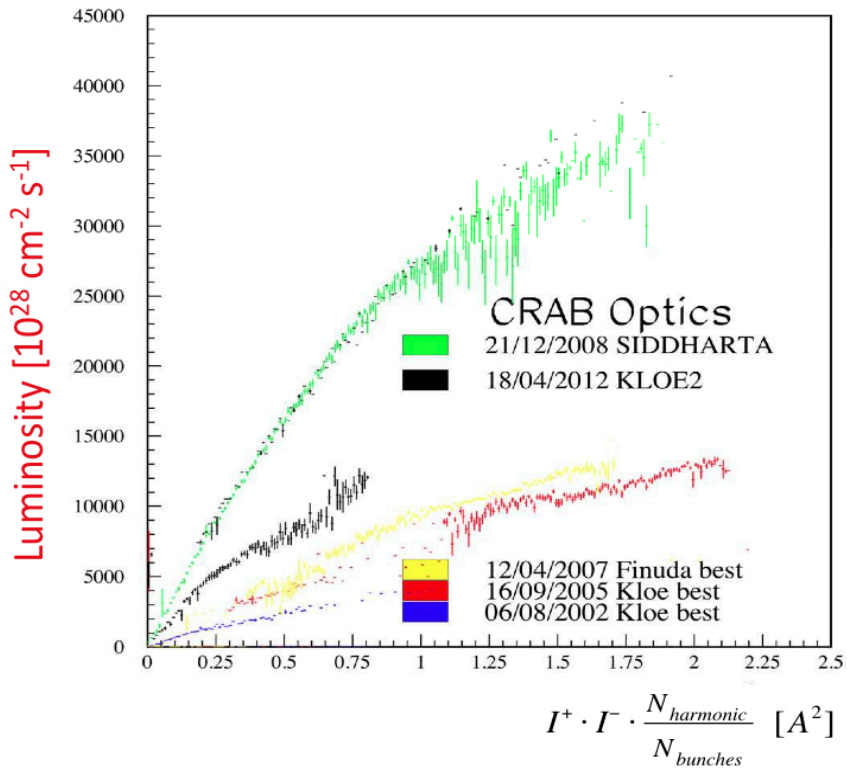
- $\gamma\gamma$ tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

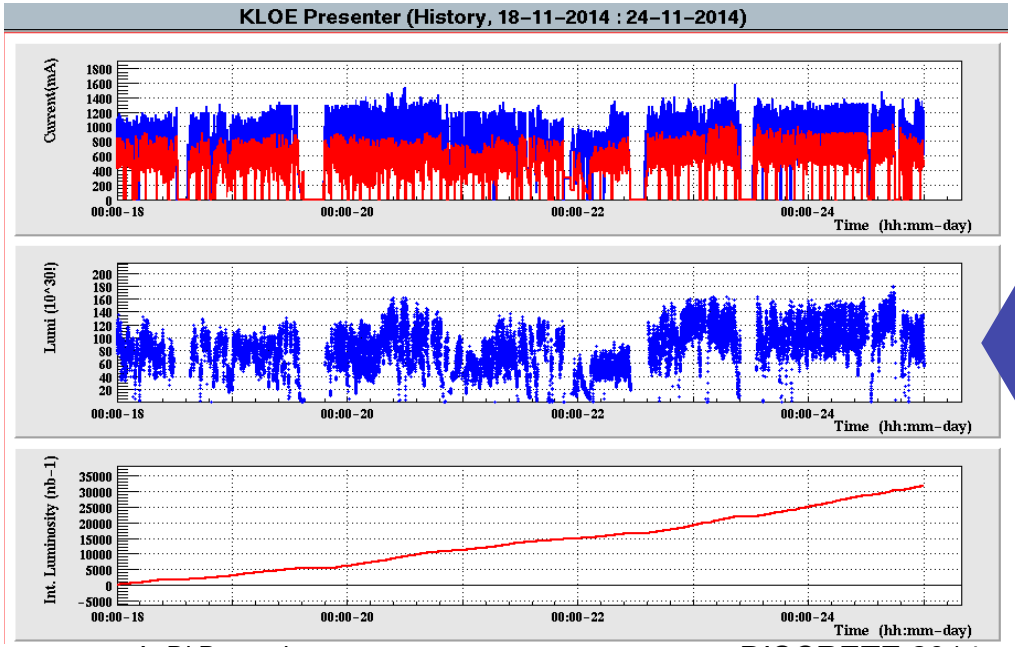
DAΦNE luminosity upgrade

- **DAΦNE upgrade (2008): new interaction scheme; large beam crossing angle + crabbed waist sextupoles**

- **In the last years a large consolidation and maintenance program of the machine has been carried out.**

- **Commissioning of DAFNE and new KLOE-2 detectors started in Jan. 2014, and after two major stops,** (e.g. interruption of water supply from the Roman Aqueduct!) **is rapidly progressing.**



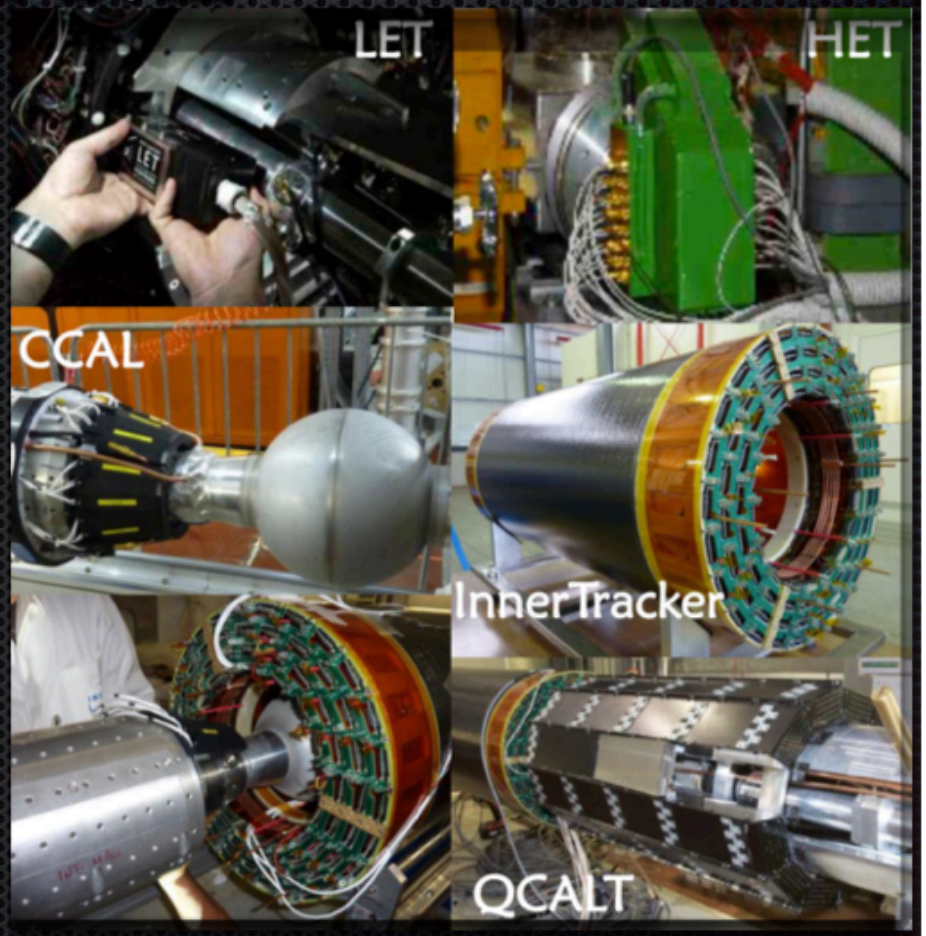


- November 2014:
- one week after restarting collisions
- **Best peak luminosity: L=1.8 x 10^{32} cm^{-2}s^{-1}**
- Improved background conditions
- Stable machine operation
- Goals:
  -collect ~1 fb^{-1} of good data by mid 2015
  -O(10 fb^{-1}) in the next 2-3 years

KLOE-2 at DAFNE

E. De Lucia's talk in the parallel session

- Calorimeter System
  - EMC – Lead / Scintillating Fibers w PMT Barrel and Endcaps
  - LET / LYSO+SiPMs
  - HET / Scintillator+PMTs
  - QCAL – Tungsten / Scintillating Tiles w SiPM
  - CCAL – LYSO Crystal w SiPM – Low- beta
- Tracking System
  - DC – Drift Chamber 4 m x 3.3 m
  - Inner Tracker – 4 Cylindrical GEM detectors
- Superconductive Magnet
  - 0.52 T solenoidal field



- Physics program [EPJC 68 (2010)]
  - Ks, η, η_s rare decays
  - Quantum interferometry
  - Dark photon search

Erika De Lucia – DISCRETE 2014 London December 2nd 2014

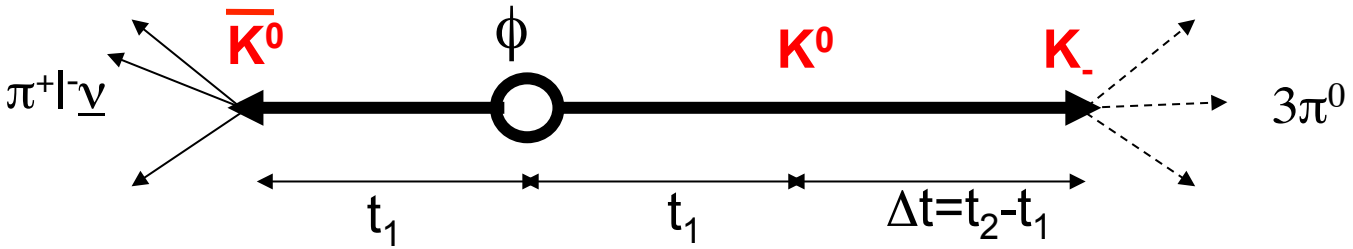
4

Direct test of Time Reversal symmetry with neutral kaons

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also orthogonal "CP states" K_+ and K_- (K_1, K_2)

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\overline{K}^0(-\vec{p})\right\rangle - \left|\overline{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[\left|K_+(\vec{p})\right\rangle\left|K_-(-\vec{p})\right\rangle - \left|K_-(\vec{p})\right\rangle\left|K_+(-\vec{p})\right\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state



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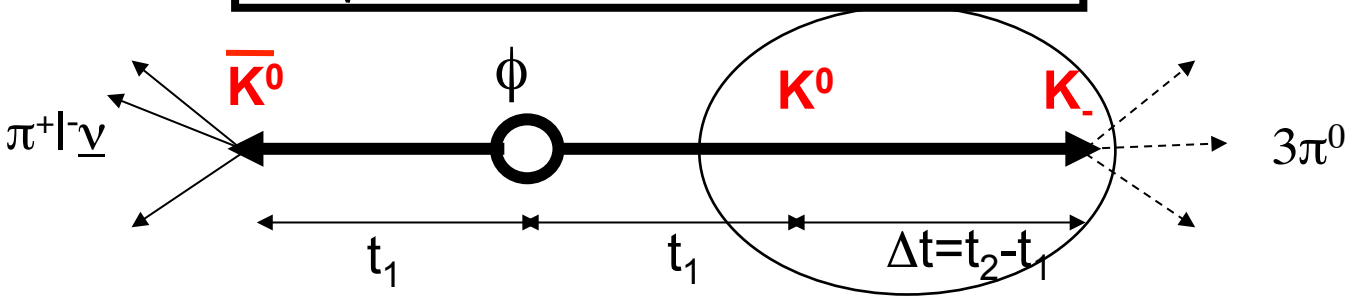

$K^0 \rightarrow K_-$ reference process

Direct test of Time Reversal symmetry with neutral kaons

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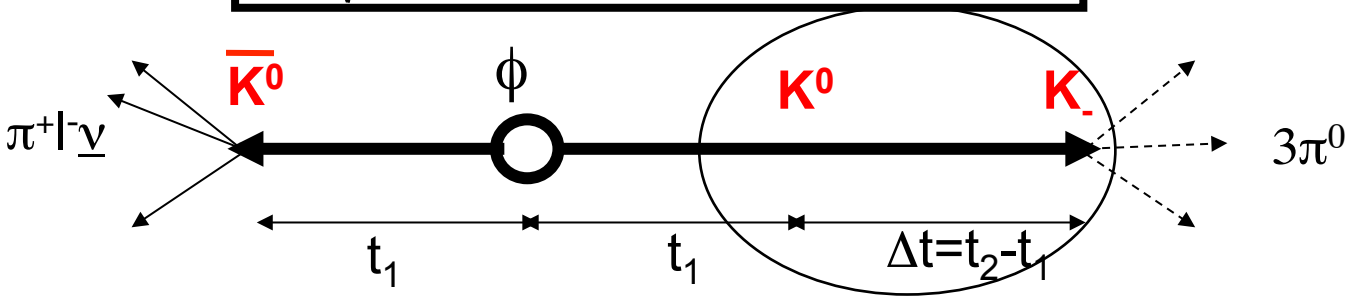

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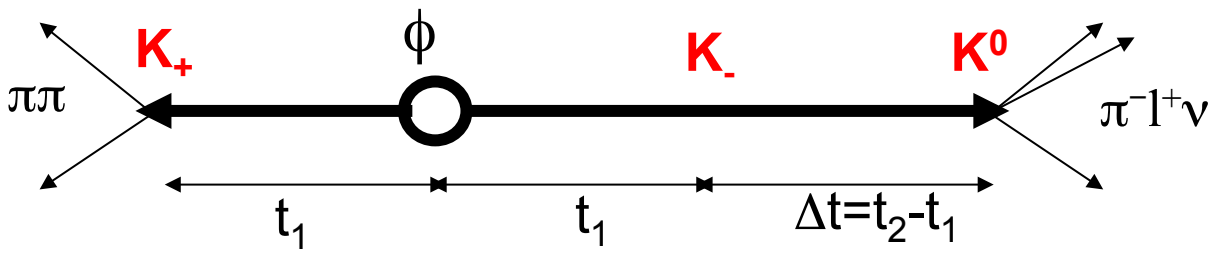

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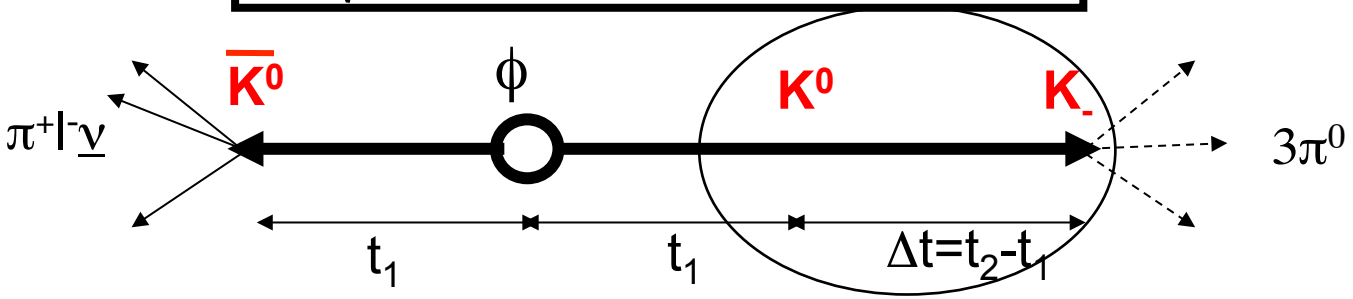
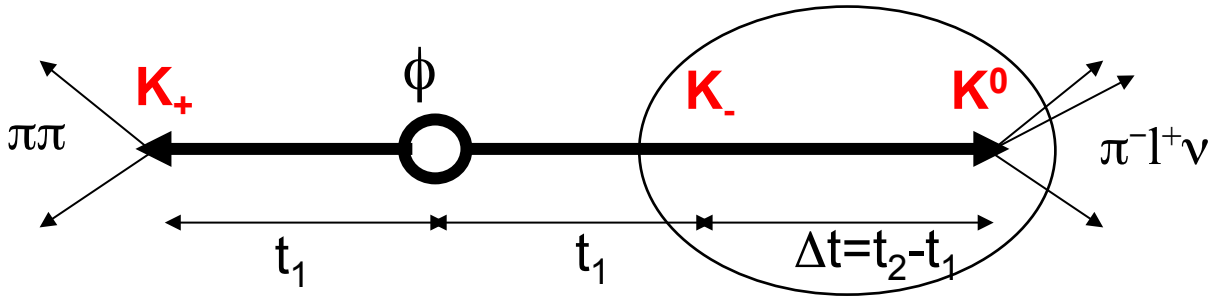


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow K^0$ T-conjugated process



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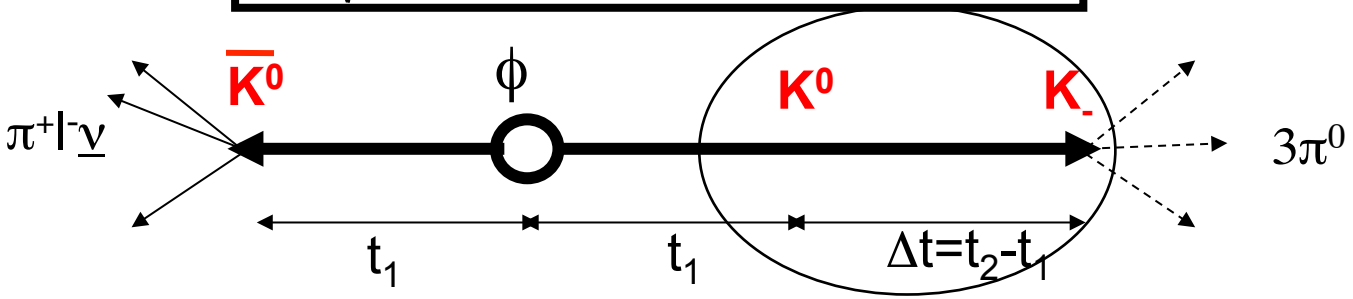
- decay as filtering measurement
- entanglement -> preparation of state

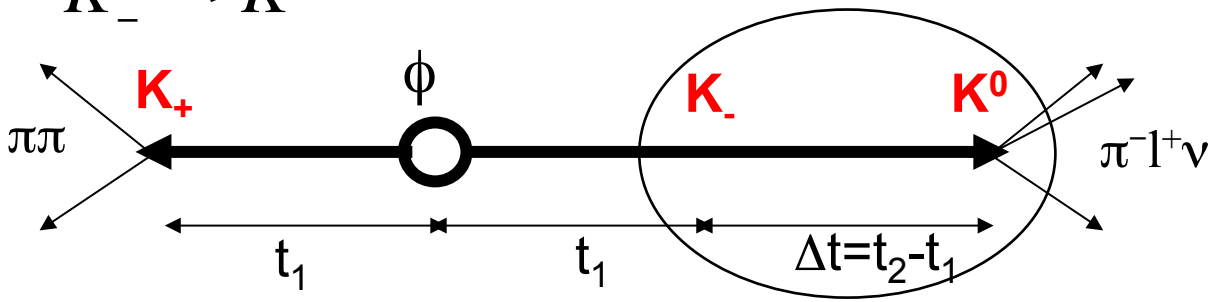


$K^0 \rightarrow K_-$ reference process

Note: CP and CPT conjugated process

$\overline{K}^0 \rightarrow K_-$ $\quad K_- \rightarrow \overline{K}^0$

$K_- \rightarrow K^0$ T-conjugated process



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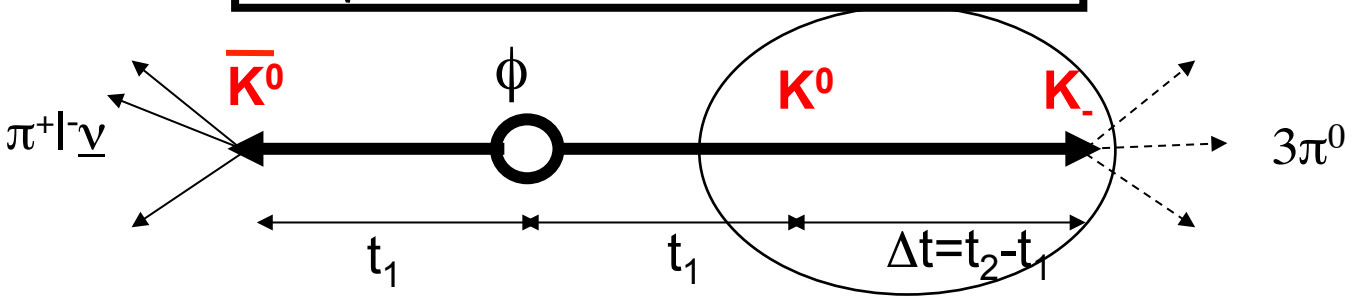


$K^0 \to K_-$ reference process

$$I(\pi\pi, l^+; \Delta t) = C(\pi\pi, l^+) \times P[K_-(0) \to K^0(\Delta t)]$$

In general with $f_{\underline{X}}$ decayng before f_Y, i.e. $\Delta t>0$:

$$I(f_{\bar{X}}, f_Y; \Delta t) = C(f_{\bar{X}}, f_Y) \times P\left[\mathrm{K_X}(0) \to \mathrm{K_Y}(\Delta t)\right]$$

with $C(f_{\bar{X}}, f_Y) = \frac{1}{2(\Gamma_S + \Gamma_L)}\left|\langle f_{\bar{X}}|T|\bar{\mathrm{K}}_\mathrm{X}\rangle\langle f_Y|T|\mathrm{K_Y}\rangle\right|^2$

Direct test of Time Reversal symmetry with neutral kaons

T symmetry test

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\bar{K}^0 \to K_-$	$(\ell^+, \pi^0\pi^0\pi^0)$	$K_- \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_+ \to K^0$	$(\pi^0\pi^0\pi^0, \ell^+)$	$K^0 \to K_+$	$(\ell^-, \pi\pi)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_- \to K^0$	$(\pi\pi, \ell^+)$	$K^0 \to K_-$	$(\ell^-, \pi\pi)$

One can define the following ratios of probabilities:

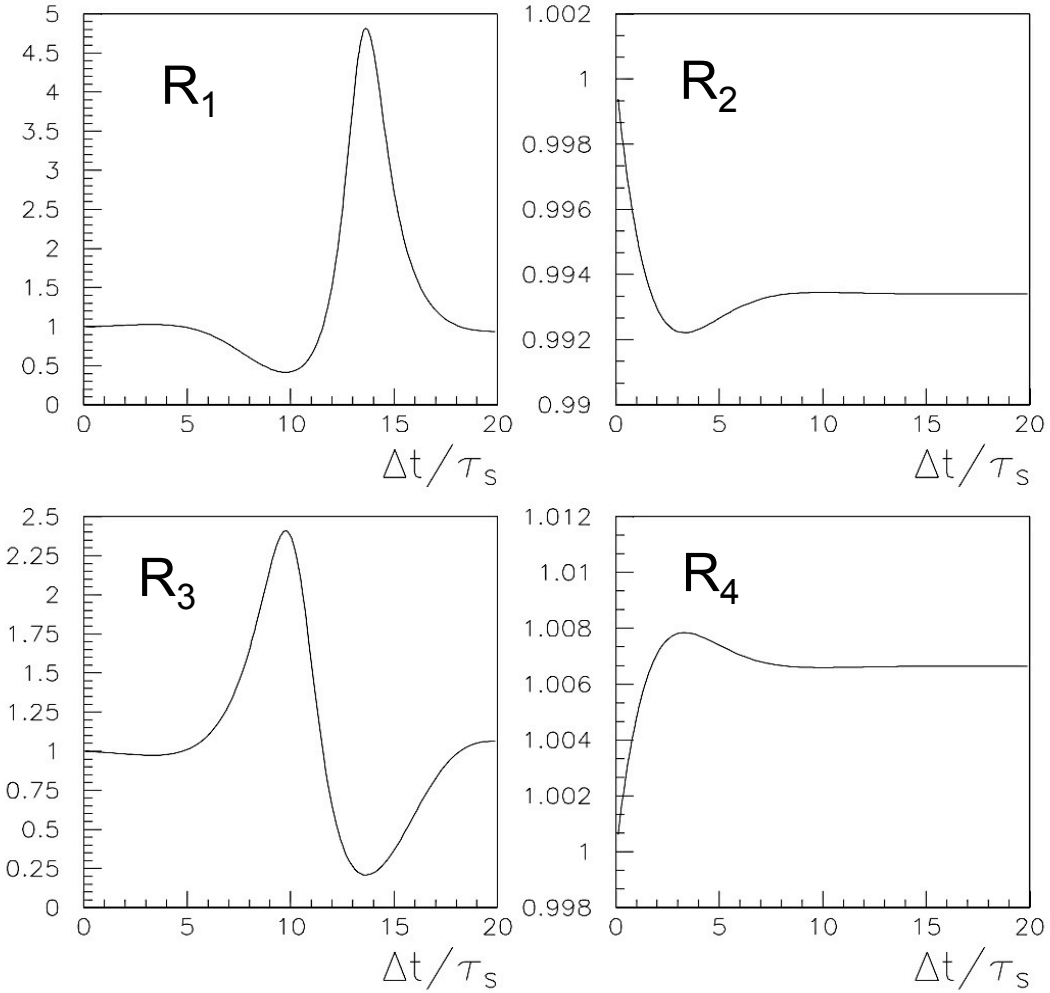
$$
\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \ .
\end{aligned}
$$

Any deviation from R_i=1 constitutes a violation of T-symmetry

J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102

Direct test of Time Reversal symmetry with neutral kaons

Any deviation from R_i=1 constitutes
a direct evidence of T-symmetry violation



$R_i(\Delta t=0)=1$

$R_2(\Delta t>>\tau_S)=1-4Re(\varepsilon)$
$R_4(\Delta t>>\tau_S)=1+4Re(\varepsilon)$

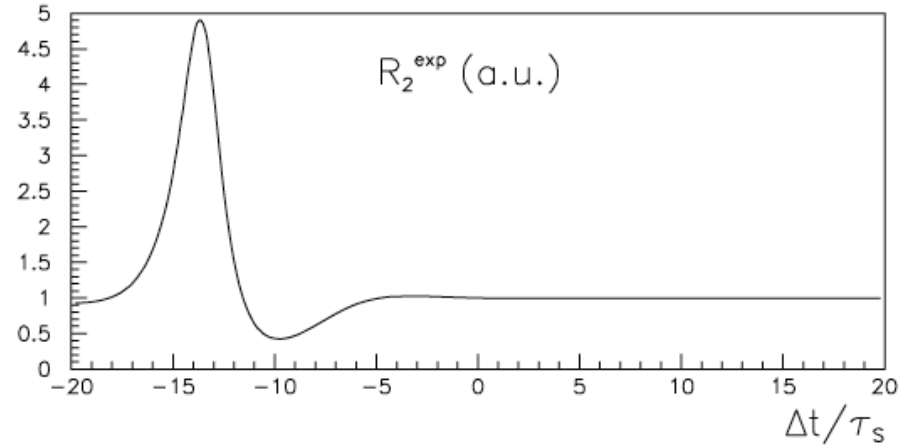
Direct test of Time Reversal symmetry with neutral kaons

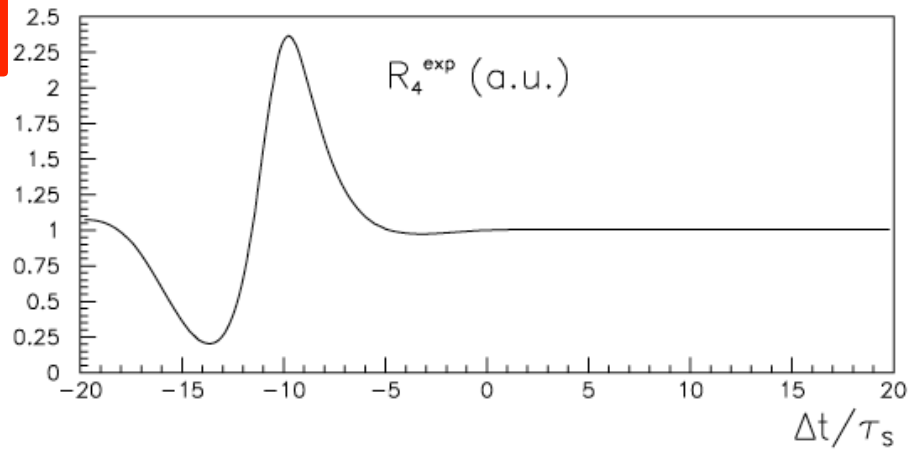
$$R_1^{\rm exp}(\Delta t) \equiv \frac{I(\ell^-, \pi\pi; \Delta t)}{I(3\pi^0, \ell^+; \Delta t)} = R_1(\Delta t) \times \frac{C(\ell^-, \pi\pi)}{C(3\pi^0, \ell^+)}$$

$$R_2^{\rm exp}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_2(\Delta t) \times \frac{C(\ell^-, 3\pi^0)}{C(\pi\pi, \ell^+)}$$

$$R_3^{\rm exp}(\Delta t) \equiv \frac{I(\ell^+, \pi\pi; \Delta t)}{I(3\pi^0, \ell^-; \Delta t)} = R_3(\Delta t) \times \frac{C(\ell^+, \pi\pi)}{C(3\pi^0, \ell^-)}$$

$$R_4^{\rm exp}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_4(\Delta t) \times \frac{C(\ell^+, 3\pi^0)}{C(\pi\pi, \ell^-)}$$





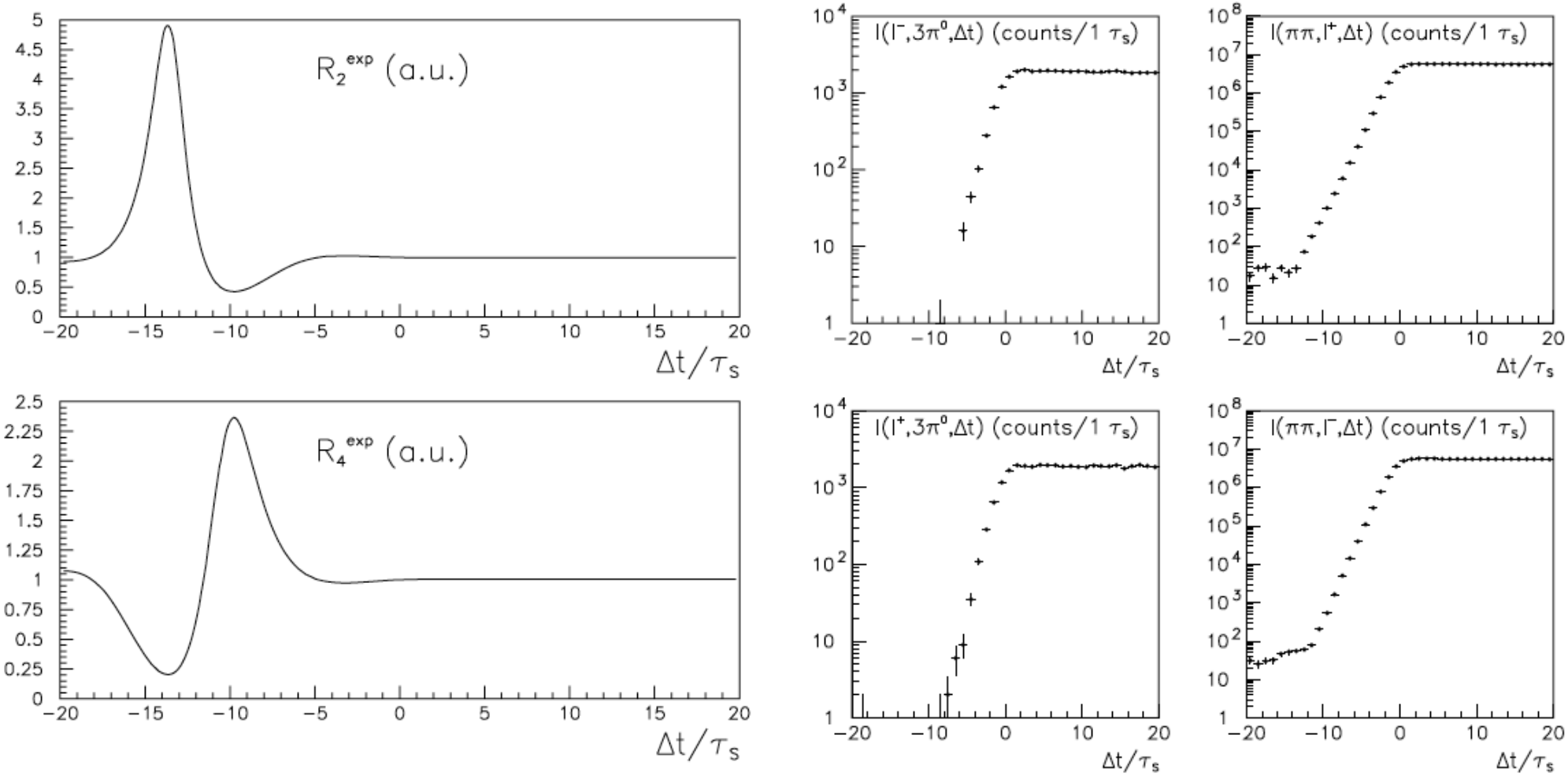
In practice two measurable ratios with $\Delta t < 0$ or > 0

$$R_2^{\rm exp}(-\Delta t) = \frac{1}{R_3^{\rm exp}(\Delta t)} = \frac{1}{R_3(\Delta t)} \times \frac{C(3\pi^0, \ell^-)}{C(\ell^+, \pi\pi)},$$

$$R_4^{\rm exp}(-\Delta t) = \frac{1}{R_1^{\rm exp}(\Delta t)} = \frac{1}{R_1(\Delta t)} \times \frac{C(3\pi^0, \ell^+)}{C(\ell^-, \pi\pi)}.$$

Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



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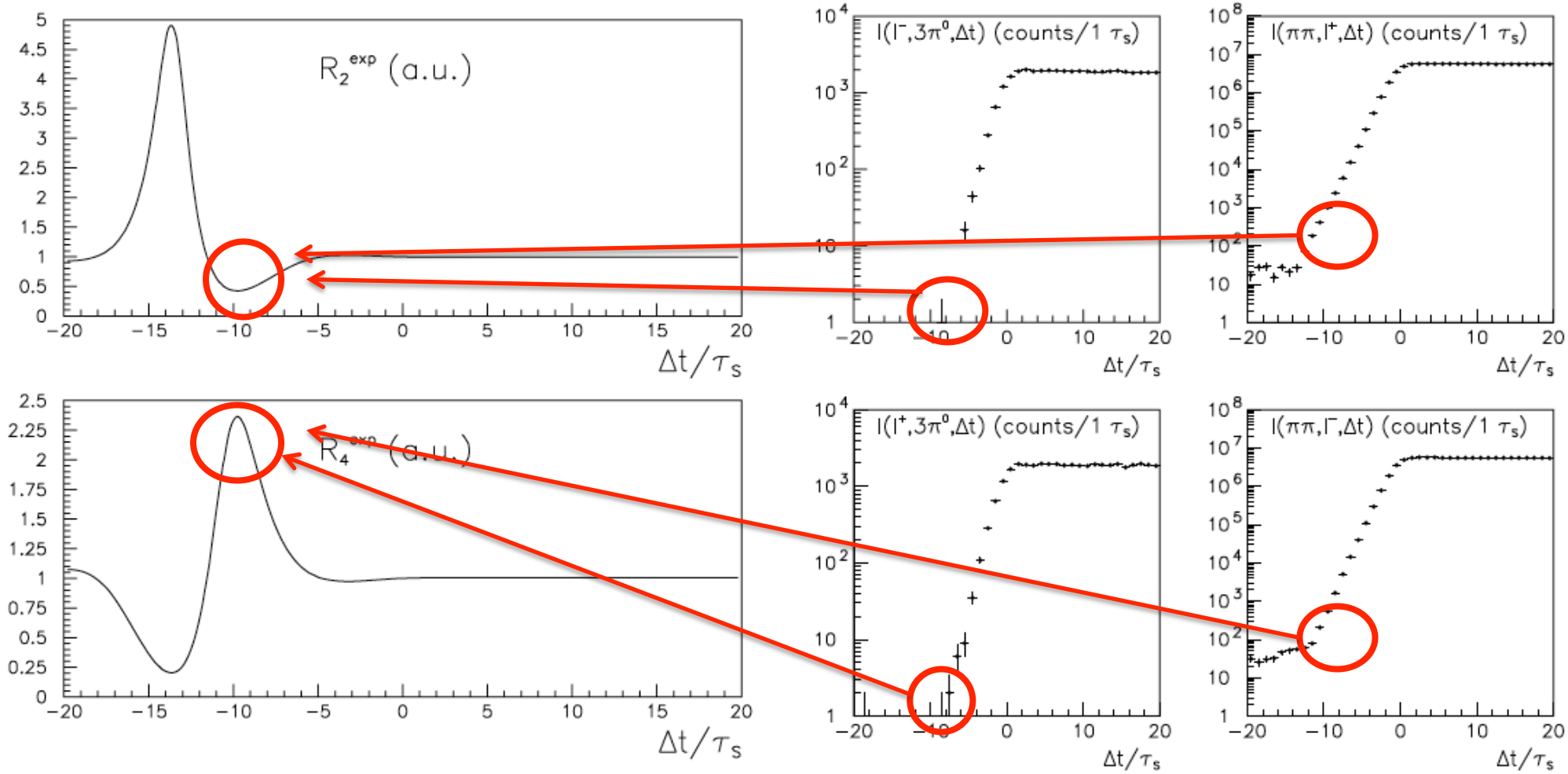

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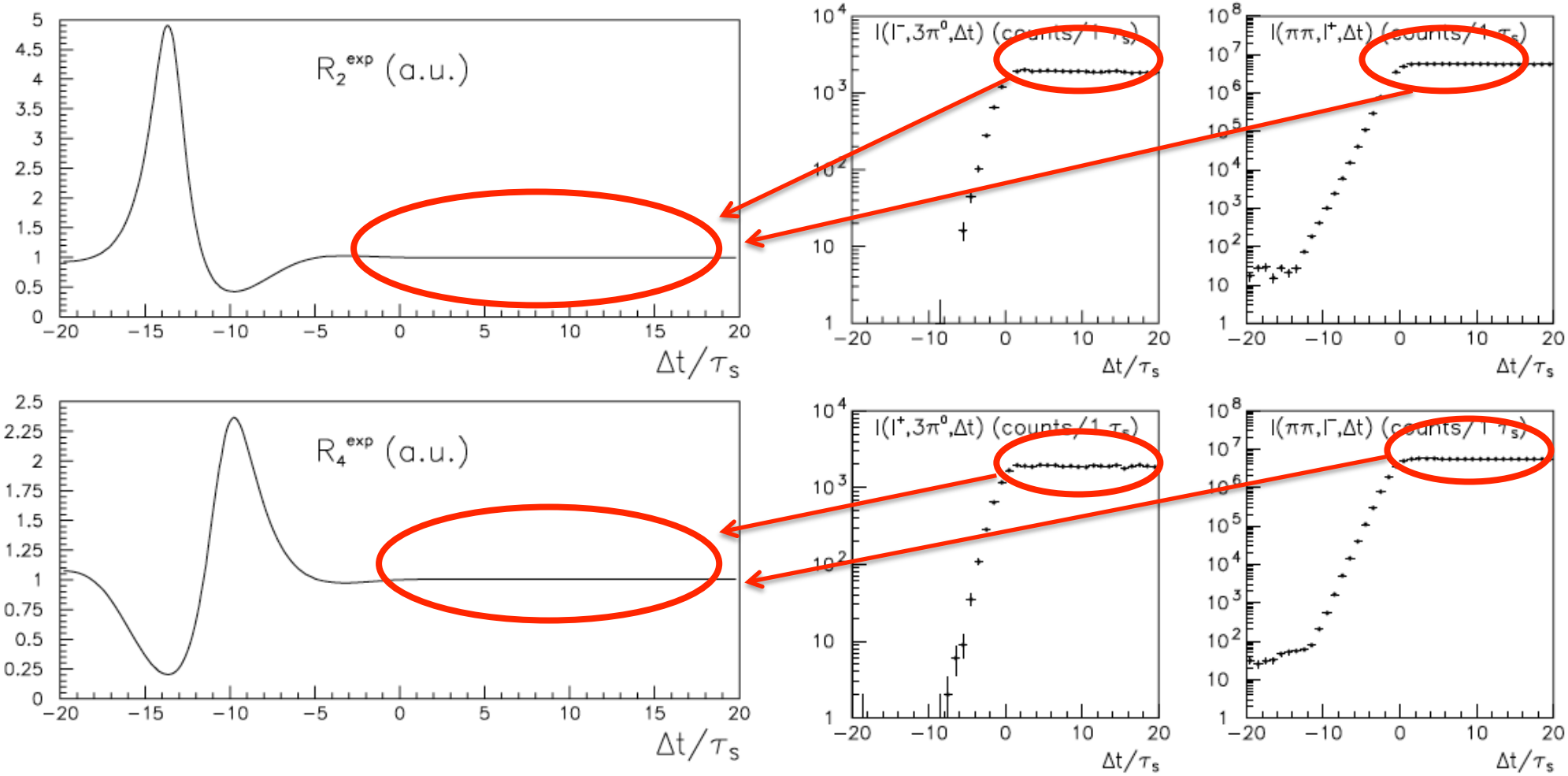

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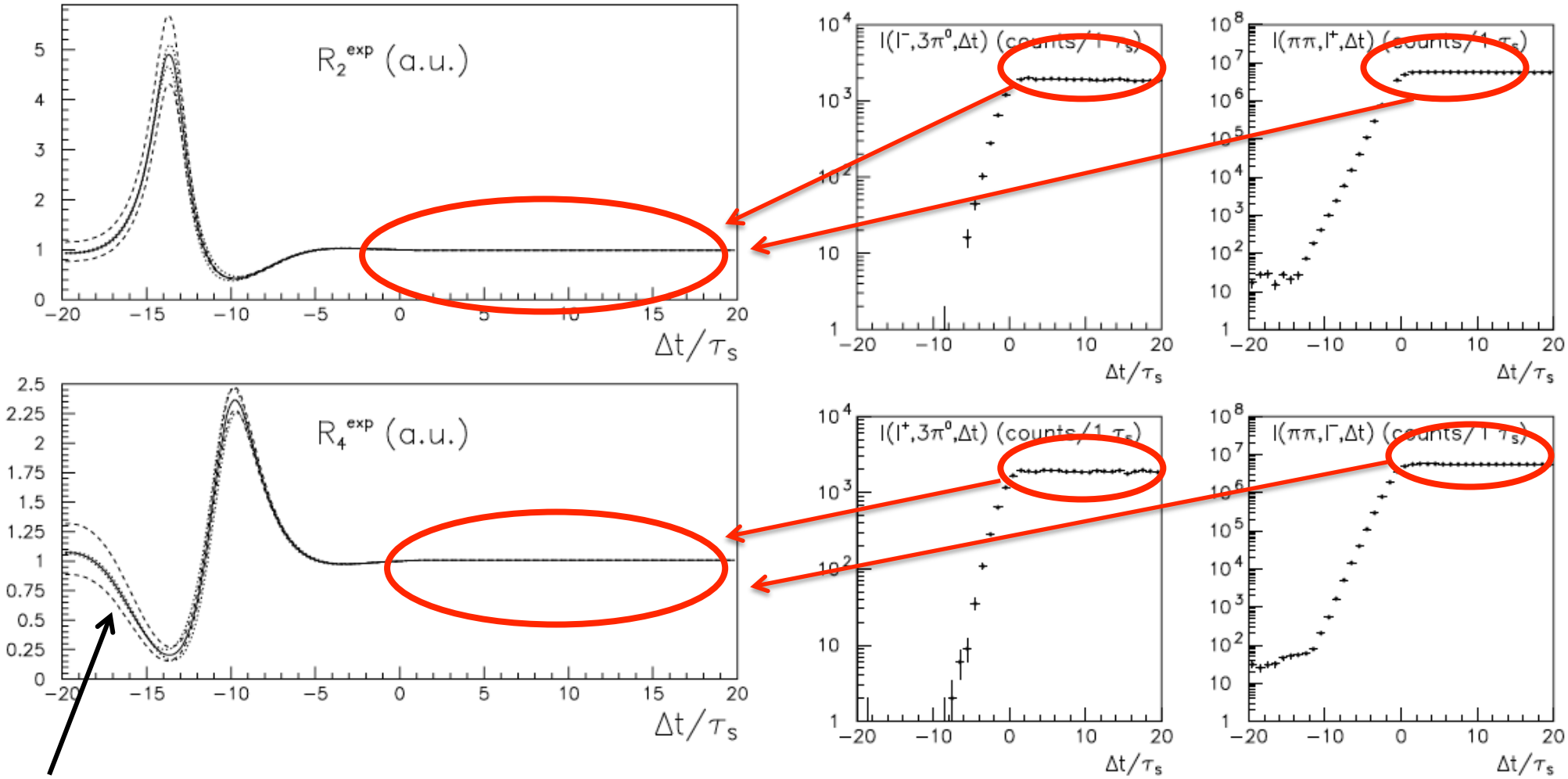
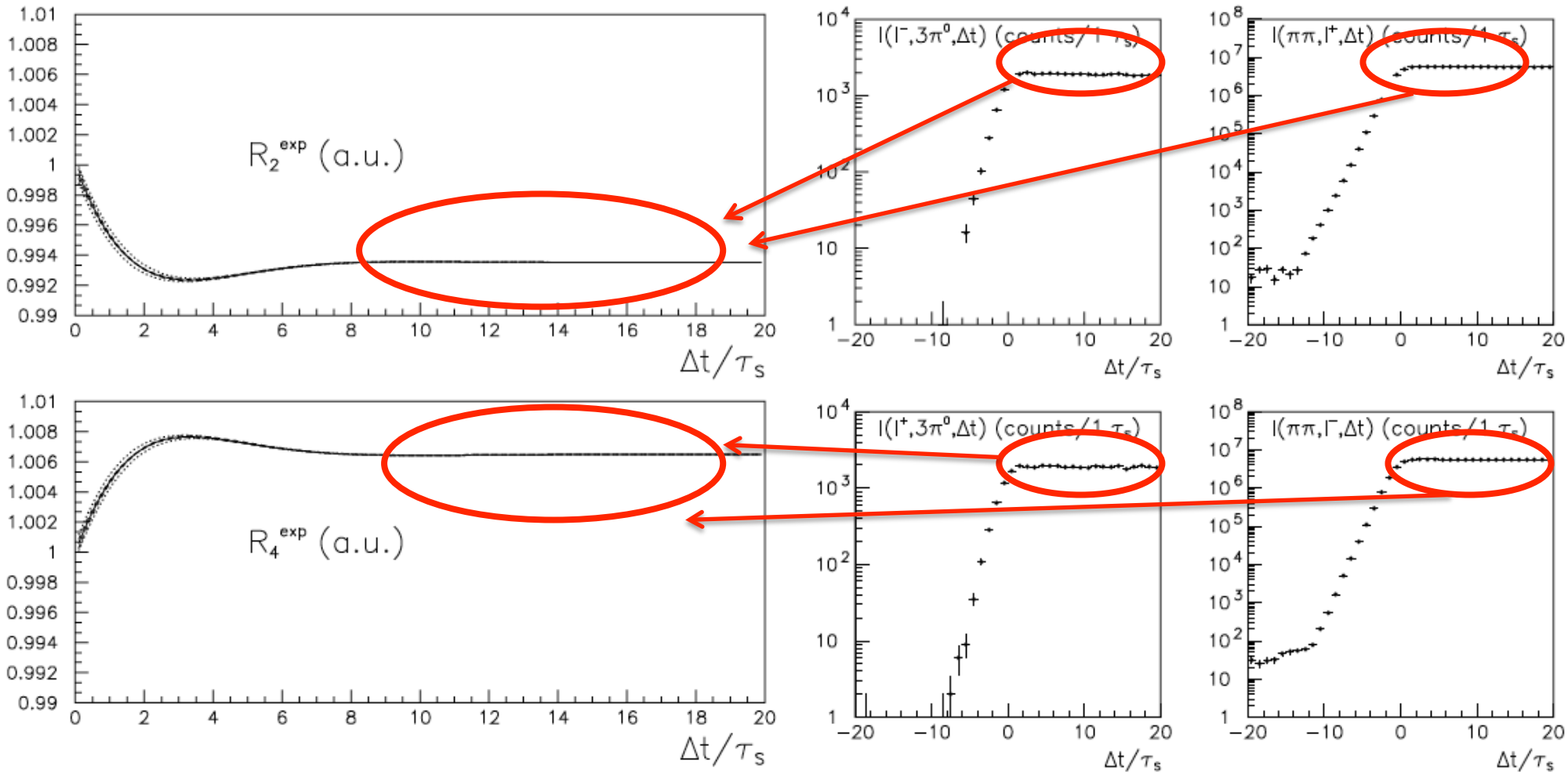


Modifications due to direct CP violation effects have to be evaluated (release of the orthogonality condition of K_+,K_-), they could spoil the significance of the T test.

Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



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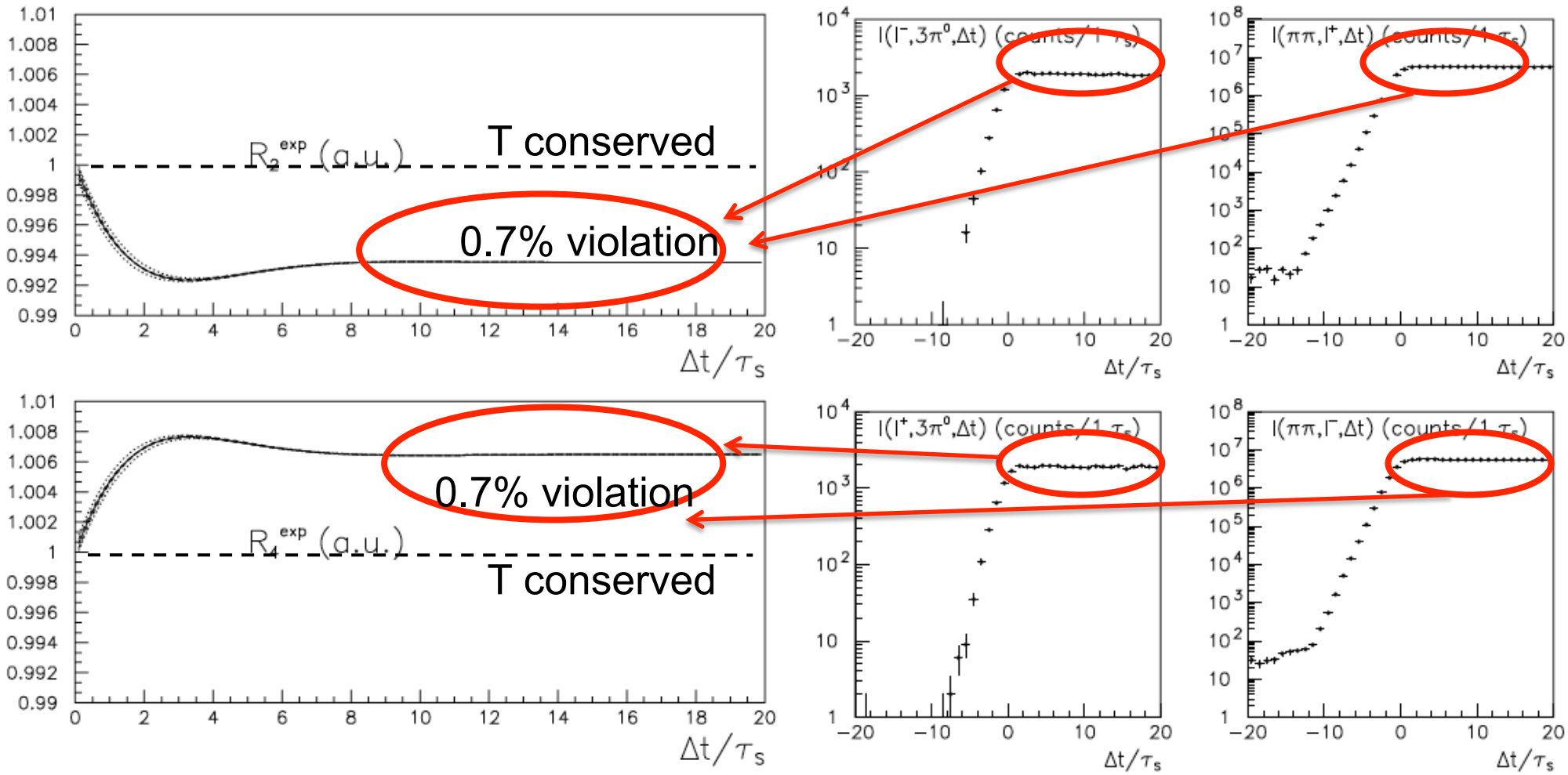

$R_2(\Delta t >> \tau_S) = 1 - 4\mathrm{Re}(\varepsilon) \sim 0.993$

$R_4(\Delta t >> \tau_S) = 1 + 4\mathrm{Re}(\varepsilon) \sim 1.007$

Direct test of Time Reversal symmetry with neutral kaons

Integrating in a Δt region between 0 and 300 τ_S =>
stat. significance of 4.4, 6.2, 8.8 σ with L=5, 10, 20 fb^{-1} (full efficiency)

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pros:
in the "plateau" region the impact of direct CP violation effects on the assumption of orthogonality of K+ and K- states has been evaluated => negligible

cons:
-in the "plateau" region one needs to measure the absolute value of R_i.
Assuming no CPT violation in semileptonic decays:

$$\frac{C(\ell^-, 3\pi^0)}{C(\pi\pi, \ell^+)} \simeq \frac{C(\ell^+, 3\pi^0)}{C(\pi\pi, \ell^-)} \simeq \frac{\mathrm{BR}(\mathrm{K_L} \to 3\pi^0)}{\mathrm{BR}(\mathrm{K_S} \to \pi\pi)} \frac{\Gamma_L}{\Gamma_S} \equiv D.$$

$$R_2(\Delta t) = \frac{R_2^{\exp}(\Delta t)}{D},$$

$$R_4(\Delta t) = \frac{R_4^{\exp}(\Delta t)}{D}.$$

- It is needed to measure the constant D with ~ 0.1% precision, i.e. BRs and K_S, K_L lifetimes
- in the "plateau" region effect proportional to Re(ε)

T test could be feasible at KLOE-2 @ DAΦNE with L=O(10 fb^{-1})

Direct test of Time Reversal symmetry with neutral kaons

CPT symmetry test

Reference		*CPT*-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$

One can define the following ratios of probabilities:

$$
\begin{aligned}
R_{1,\mathcal{CPT}}(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_{2,\mathcal{CPT}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \\
R_{3,\mathcal{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_{4,\mathcal{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]
\end{aligned}
$$

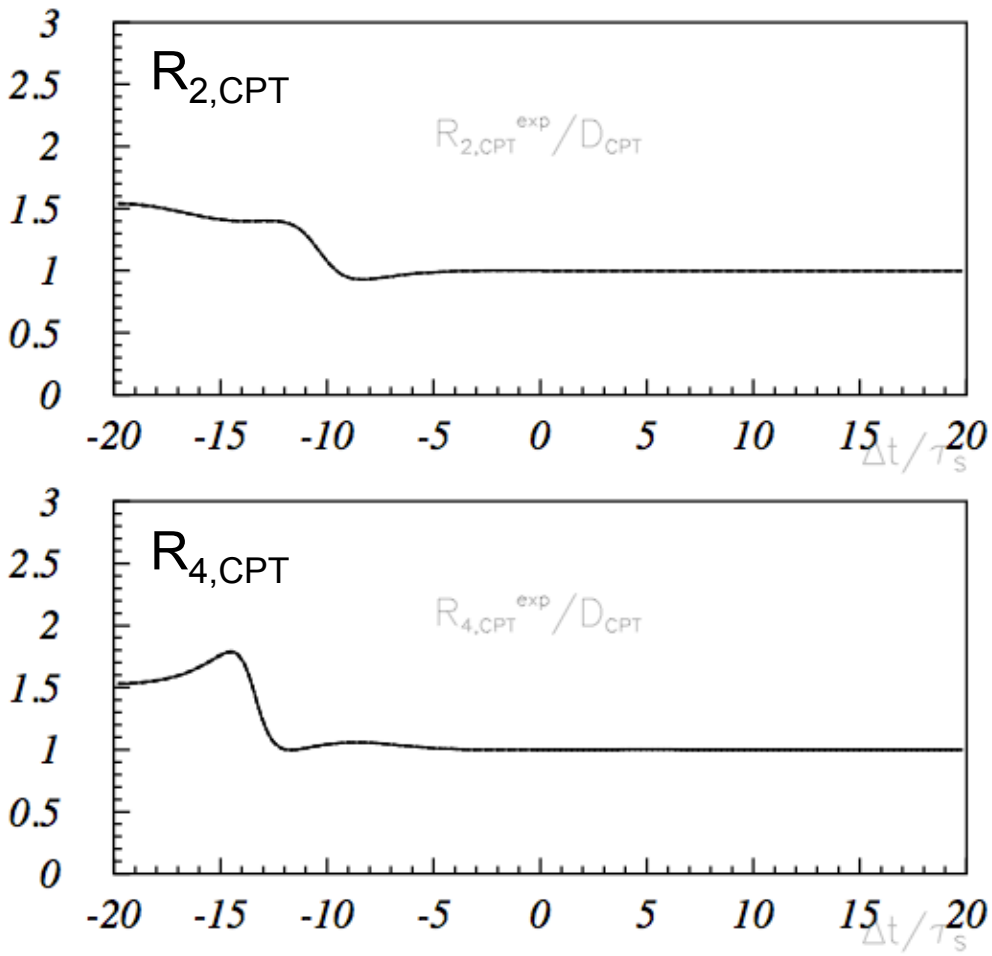
Any deviation from $R_{i,CPT}=1$ constitutes a violation of T-symmetry

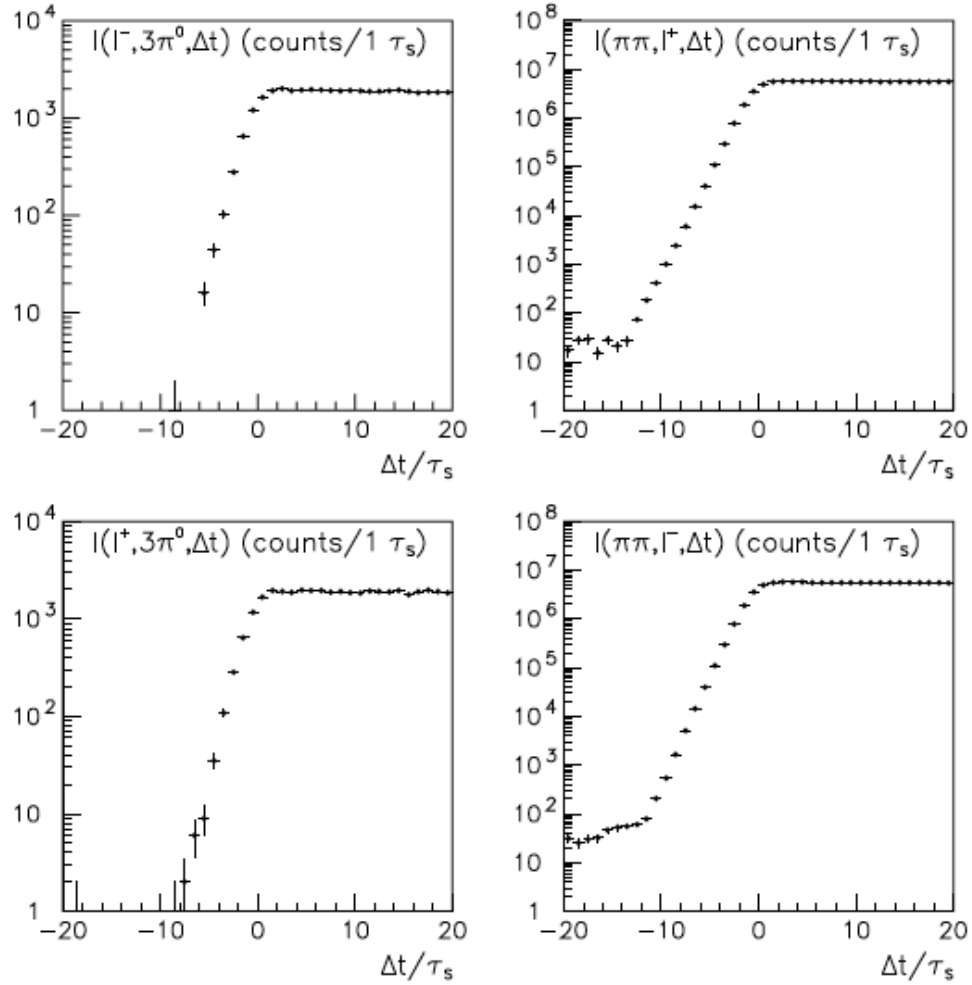
J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102 **J. Bernabeu, A.D.D. in preparation**

Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$

toy MC with $L=10\ fb^{-1}$





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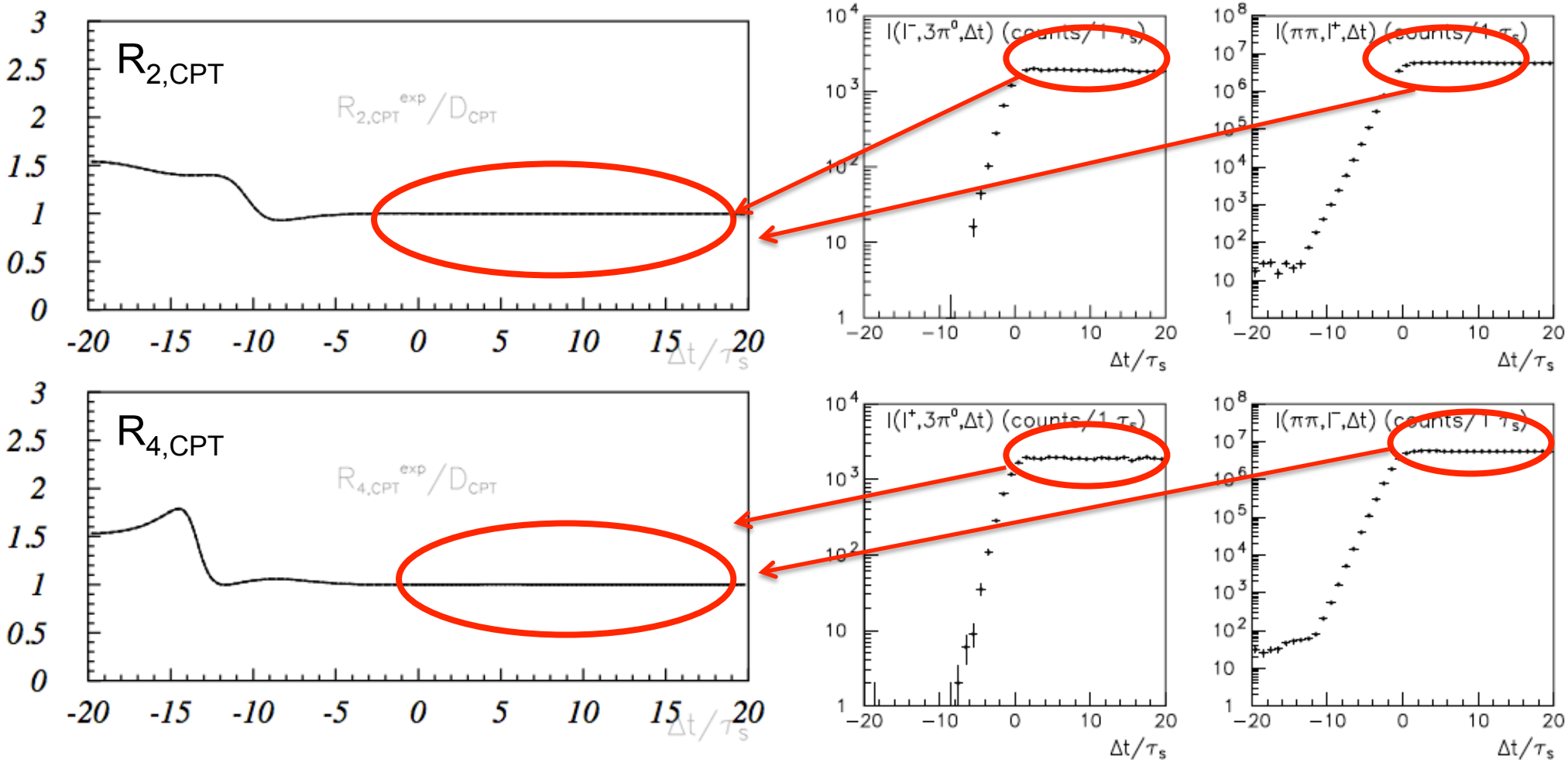

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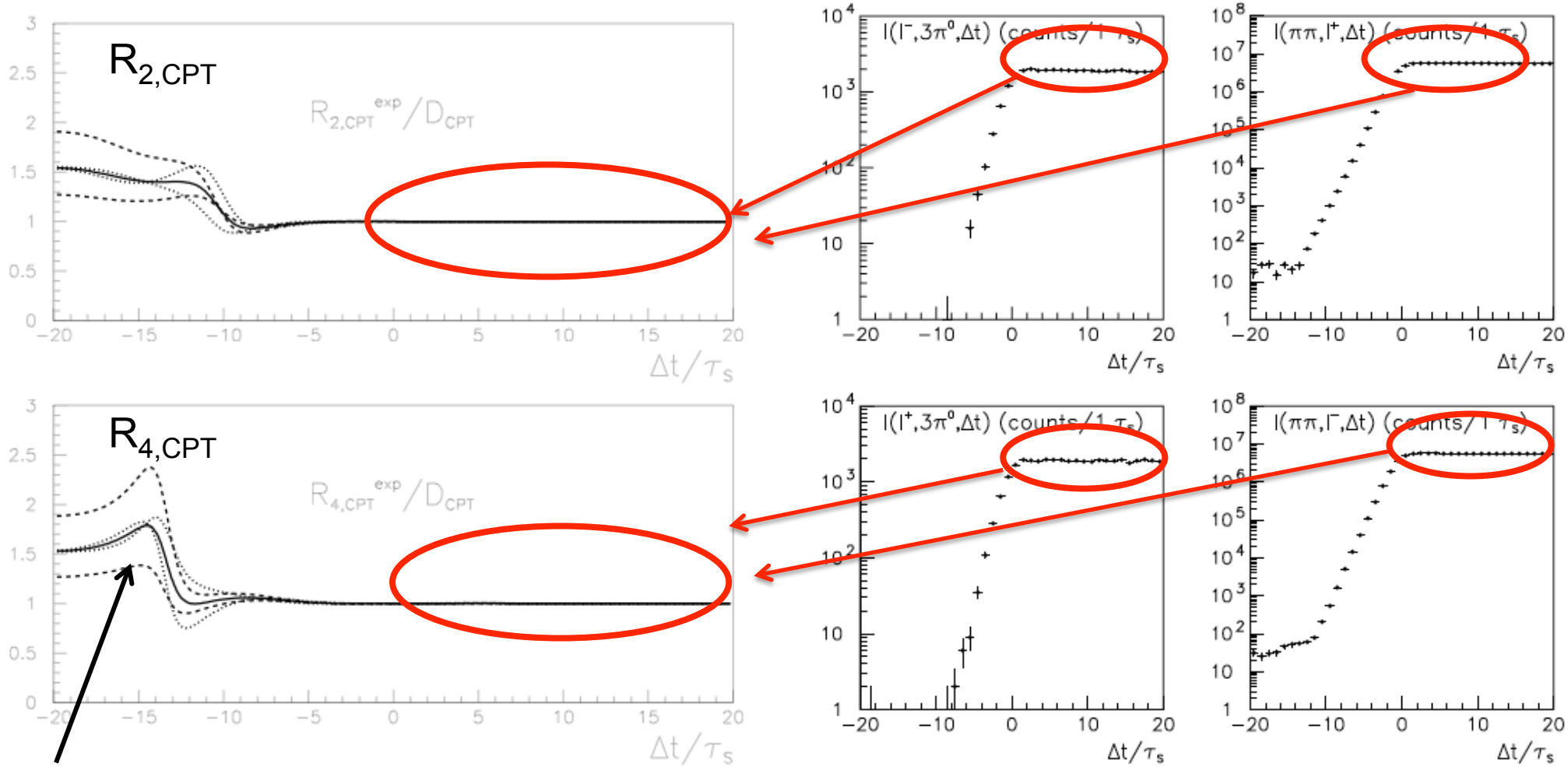
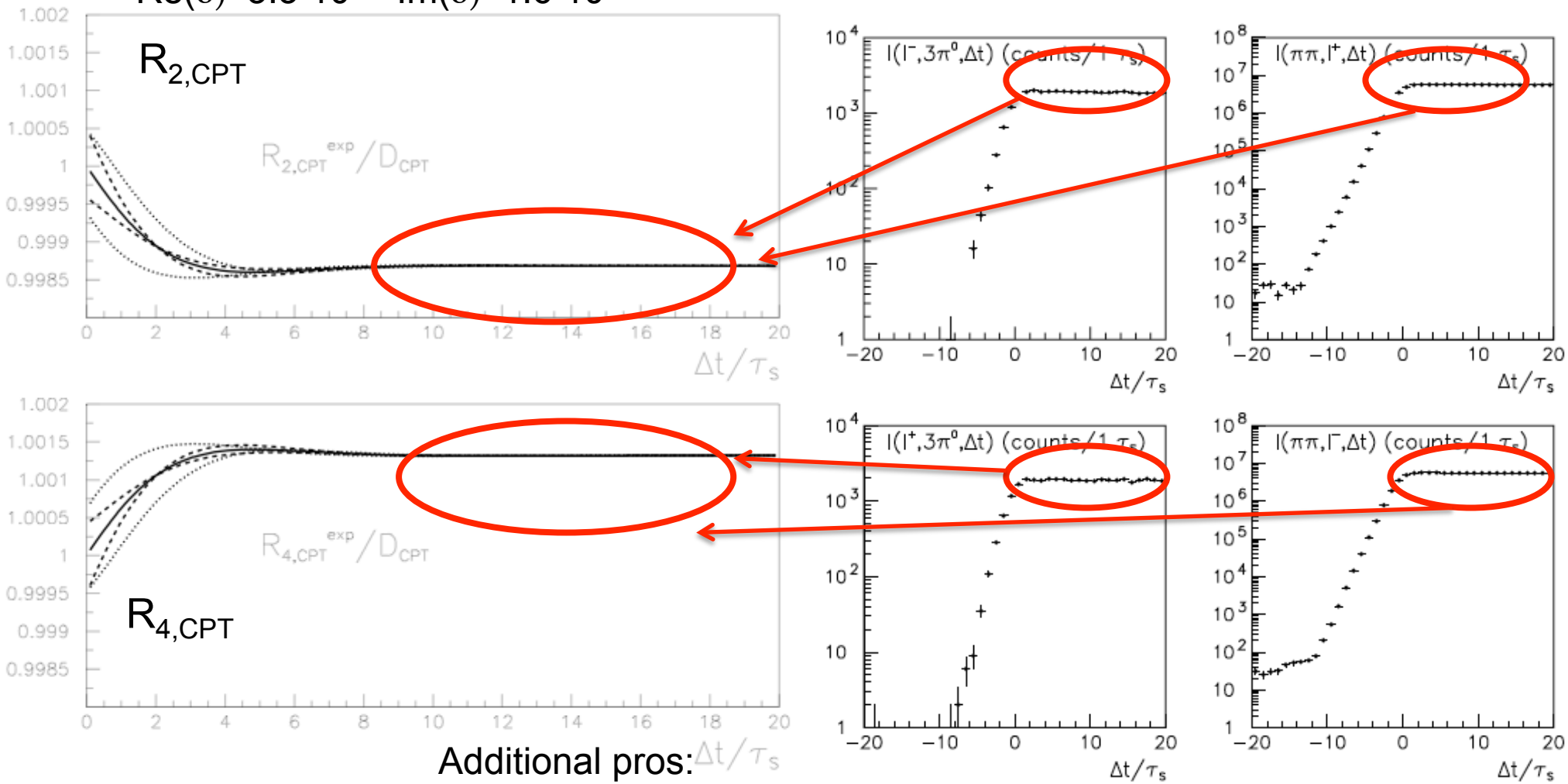


Modifications due to direct CP violation effects have to be evaluated (release of the orthogonality condition of K_+,K_-), they could spoil the significance of the T test.

Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$

toy MC with $L=10\ fb^{-1}$



Additional pros:

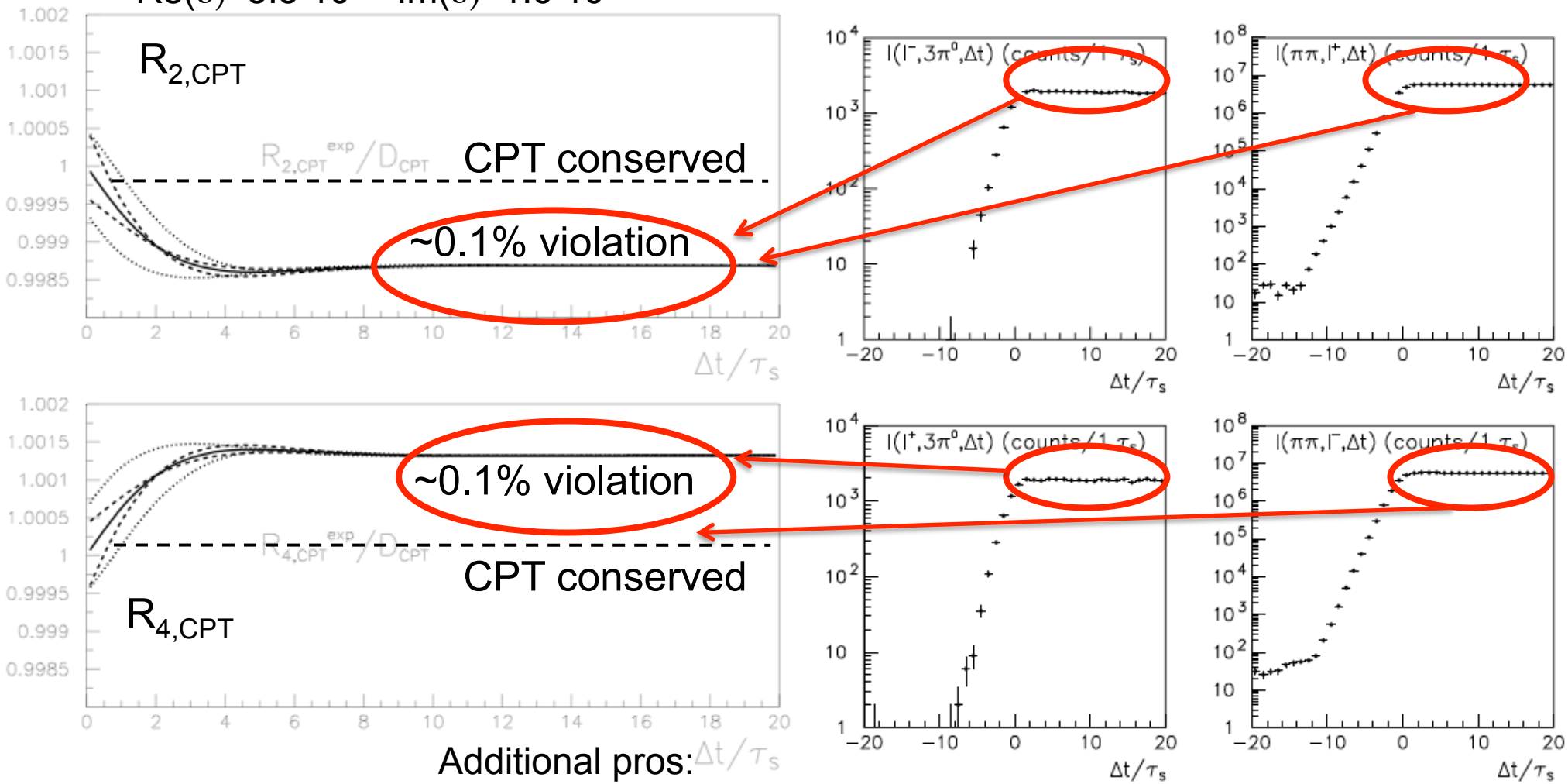
$R_{2,CPT}(\Delta t>>\tau_S)=1-4Re(\delta)$ - contrary to T violation, the effect $\propto \Re\delta$ does not vanish with $\Delta\Gamma \to 0$

$R_{4,CPT}(\Delta t>>\tau_S)=1+4Re(\delta)$ - No assumption on CPT violation in semileptonic decays is needed

Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$

toy MC with $L=10\ fb^{-1}$



Additional pros:

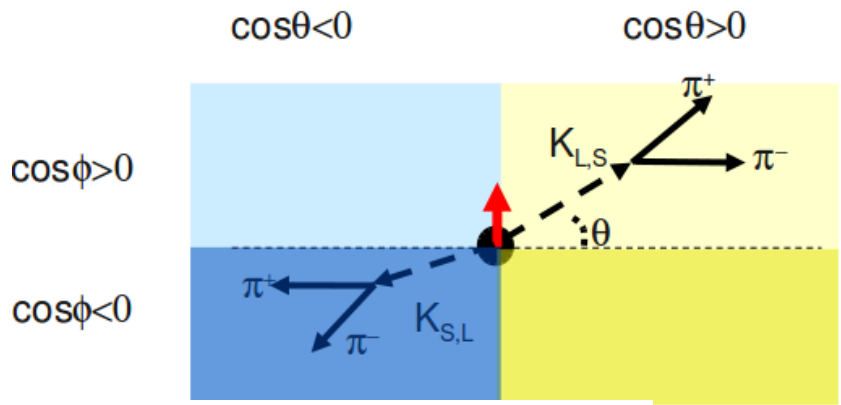
$R_{2,CPT}(\Delta t>>\tau_S)=1-4Re(\delta)$ - contrary to T violation, the effect $\propto \Re\delta$ does not vanish with $\Delta\Gamma \to 0$

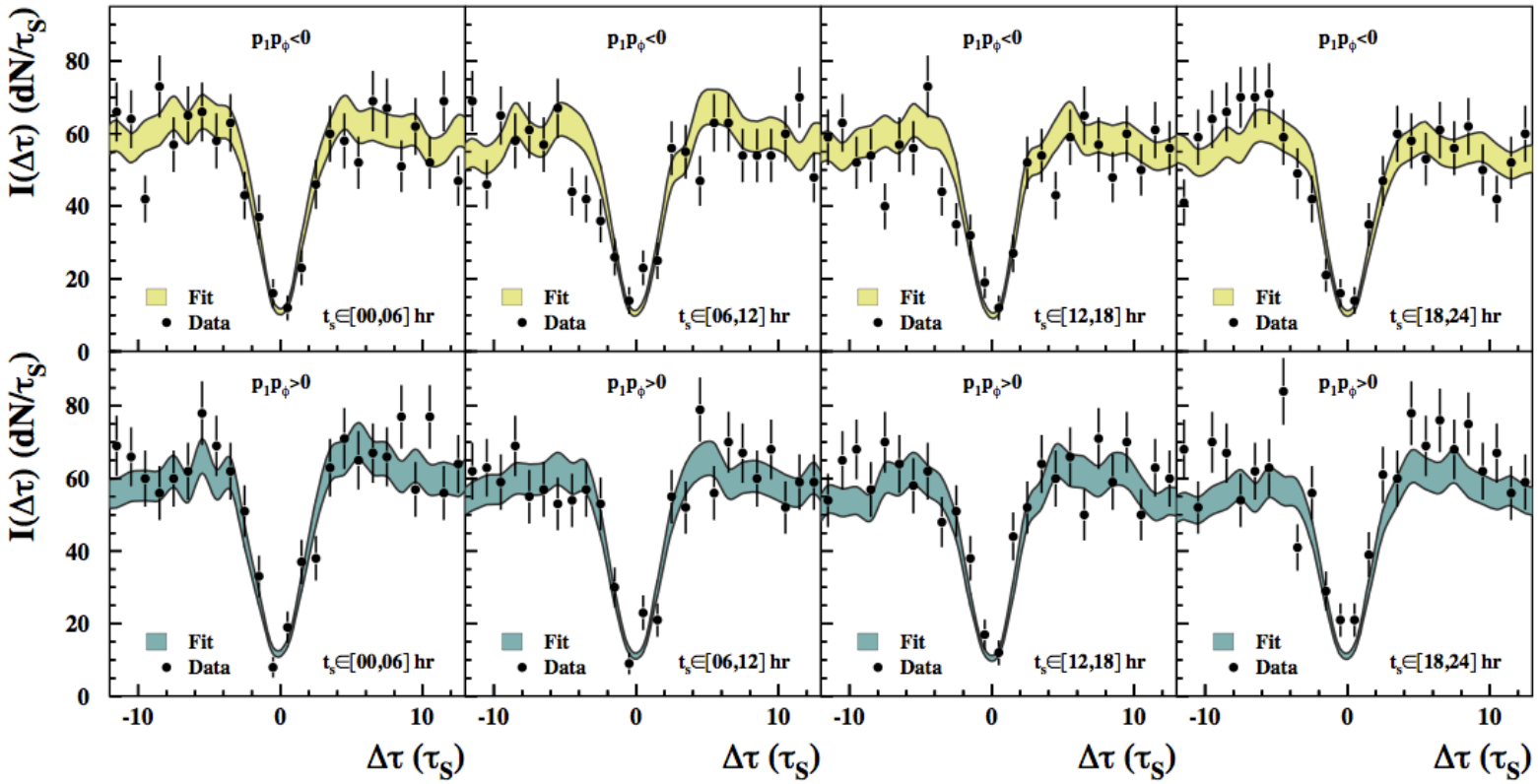
$R_{4,CPT}(\Delta t>>\tau_S)=1+4Re(\delta)$ - No assumption on CPT violation in semileptonic decays is needed

Search for CPTV and Lorentz invariance breaking

$$\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta \vec{a} \right) / \Delta m$$

Data divided in
4 sidereal time bins x 2 angular bins
Simultaneous fit of the Δt distributions to extract Δa_μ parameters





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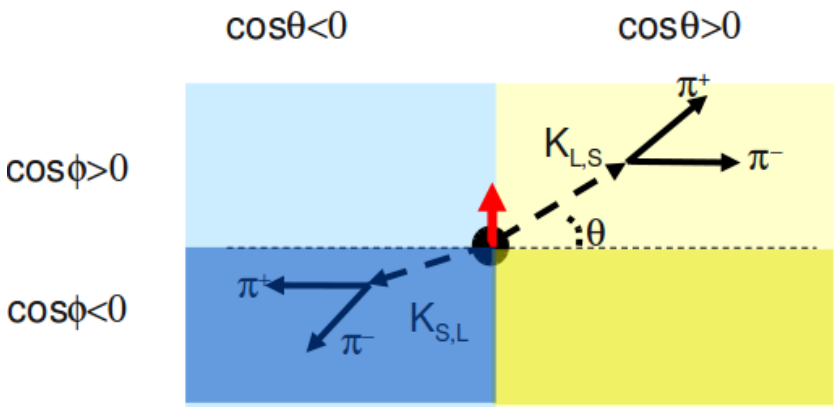

Par	Cut stability	Fit Range	Bkg. subtr	KLOE ref. frame	**Total**
Δa_0	1.1	2.4	1.3	1.0	**3.1**
Δa_X	0.3	0.3	0.4	0.2	**0.6**
Δa_Y	0.2	0.3	0.2	0.2	**0.5**
Δa_Z	0.2	0.2	0.4	0.4	**0.6**

with L=1.7 fb^{-1} KLOE final result
PLB 730 (2014) 89–94

$$\Delta a_0 = \left(-6.0 \pm 7.7_{STAT} \pm 3.1_{SYST}\right) \times 10^{-18} \text{ GeV}$$
$$\Delta a_X = \left(0.9 \pm 1.5_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Y = \left(-2.0 \pm 1.5_{STAT} \pm 0.5_{SYST}\right) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Z = \left(-3.1 \pm 1.7_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$

These are the most precise measurements in the quark sector of Standard Model Extension
(Kostelecky PRD 61 (1999) 016002)
In B,D systems:
$\sigma(\Delta a\mu^{B,D})$ is $O(10^{-13})$ GeV

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled K states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$$|i\rangle \propto \left(|K^0\rangle|\bar{K}^0\rangle - |K^0\rangle|\bar{K}^0\rangle\right) + \omega\left(|K^0\rangle|\bar{K}^0\rangle + |K^0\rangle|\bar{K}^0\rangle\right)$$

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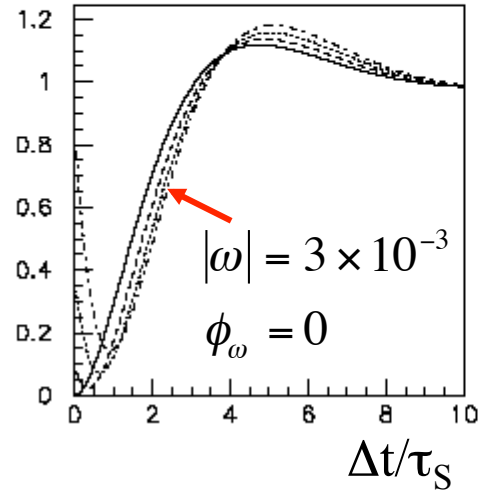
at most one expects:

$$|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}$$

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



In some microscopic models of space-time foam arising from non-critical string theory:
$\omega \sim 10^{-4} \div 10^{-5}$
[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

KLOE result

PLB 642(2006) 315
Found. Phys. 40 (2010) 852

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.}$$

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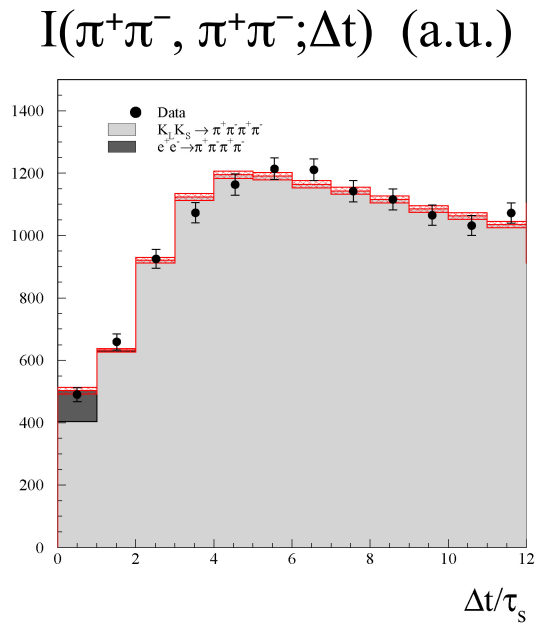

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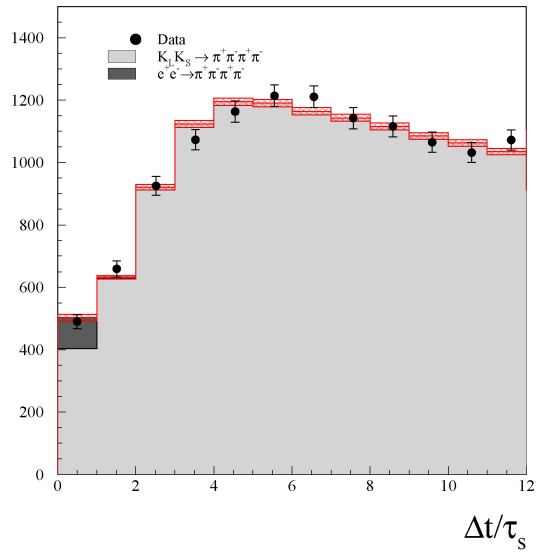

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KLOE-2 goal $\sigma(\omega) \sim O(10^{-5})$

New formulation of Bell's inequality for neutral kaons

J. Bell himself considered to use entangled K^0's to test BI !! (Varenna School, 1970)

$$\min_{\text{all } \rho \text{ sep}} S(t_1,t_2,t_3,t_4)[\rho_{\text{sep}}] \le S(t_1,t_2,t_3,t_4) \le \max_{\text{all } \rho \text{ sep}} S(t_1,t_2,t_3,t_4)[\rho_{\text{sep}}]$$

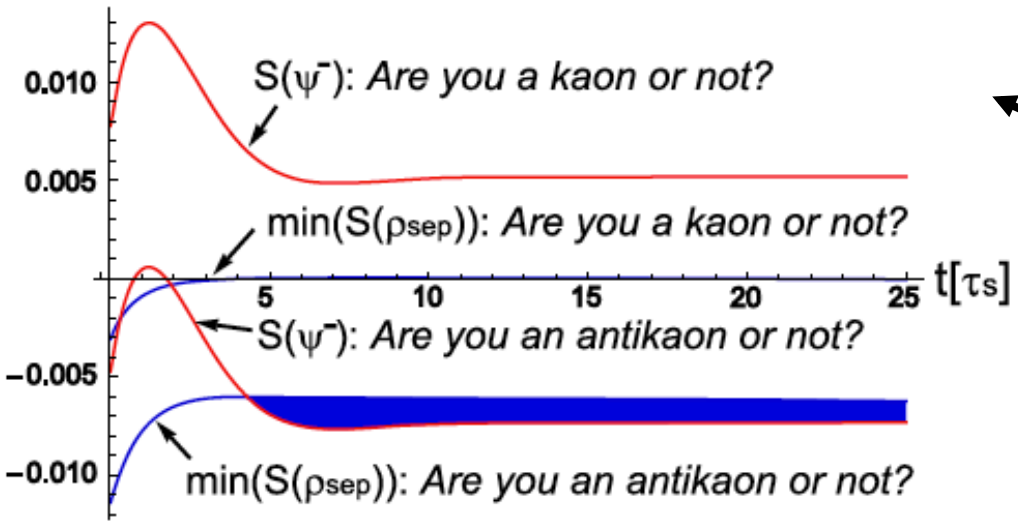
B. Hiesmayr's talk in the parallel session

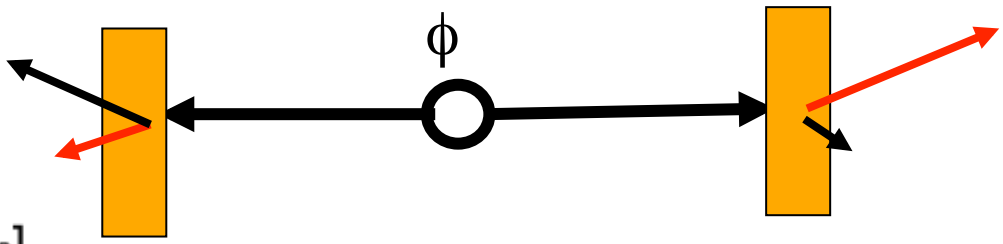
where:

$$S(t_1,t_2,t_3,t_4) = E(t_1,t_2) - E(t_1,t_3) + E(t_4,t_2) + E(t_4,t_3)$$

$$E(t_1,t_2) = 1 + 4P(K^0,t_1;K^0,t_2) - 2P(K^0,t_1;*) - 2P(*;K^0,t_2)$$

Hiesmayr, A.D.D. et al. EPJC (2012) 72:1856





In this example: t_1, t_2, t_3, t_4 ~ 5 τ_S

CP violation plays a crucial role in Bell's inequality violation: CPV -> BIV

Conclusions

- The next generation of experiments at hadron machines (NA62 and KOTO) are operational, allowing us to definitely enter the very rare kaon decay era.
- Data taking will be completed in 2-3 years from now.
- Ultra high sensitivity and precision will be essential and crucial as a probe of New Physics beyond the SM, and complementary to LHC.

- The KLOE-2 experiment at the upgraded DAFNE started taking data with the plan to collect O(10) fb^{-1} in the next 2-3 years.
- The connection of entanglement with discrete symmetries of neutral kaons is still surprising and will continue to be one of the key issues at KLOE-2 with several high precision Quantum Mechanics, CPT and T symmetries tests.

- Sometimes we are in very stormy seas....which requires great perseverance, tenacity and patience to achieve the results.